The essential elements to sustain fisheries

by

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Statements and Declarations

Declaration of originality

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The research associated with this thesis abides by the international Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of the Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

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Abstract

Healthy marine ecosystems are vital for sustaining fisheries, poverty reduction, food security, and economic development worldwide. However failure to understand ecosystem dynamics – and particularly how they change under anthropogenic impacts – underpins major ecosystem shifts across the globe. Without robust and careful governance in place, levels of stress on ecosystems and fisheries are likely to have a continuous negative impact on biodiversity and fish stock abundance. Fish stocks are subject to a plethora of human-related impacts such as overfishing, habitat destruction, pollutants, and environmental change. Without appropriate knowledge and understanding of how to sustainably manage fisheries and the ecosystems that support them, the risk of ecological failure, fishery collapse, and ultimately social collapse is large. Despite increased efforts in fisheries research and management, improvements are still needed to restore the over-exploited fisheries and ensure sustainability of all fisheries.

The foundation of this PhD thesis is to investigate how human impacts influence biodiversity and fish stock abundance, and the management tools that can be used to sustain fisheries. This project takes a holistic approach to the risk of overfishing and fisheries collapse, and what is needed to make them sustainable based on key biological, environmental, social, economic, industry, governance, and management variables and associated criteria effecting stock abundance.

Considering the complex socio-ecological interactions that affect the sustainability of marine ecosystems and fisheries, this research investigates what sources might facilitate sustainability or trigger shifts towards overfishing or even collapse. To date this kind of holistic approach has been lacking, and this thesis is intended as one step towards redressing that gap. To better understand how to sustain fisheries a mixed method approach was used, by combining a meta-analysis of 21 fisheries, a qualitative survey of 188 fisheries experts from 34 nations, and a case-study of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR was used as a case-study as the ecosystems, and fisheries, within the convention area are perceived to be well-managed.

There is a consistent emergent picture across the three analyses on how to sustain fisheries. The meta-analysis showed that the 14 sustainable fisheries identified were associated with sound biological knowledge, had a large range of management tools in place, and included some element of industry control such as a paid quota system. The survey of fisheries experts confirmed these findings as well as highlighting that there are a range of management tools that have proven efficient to sustain fisheries worldwide, if implemented and applied properly and conscientiously. Further, views of the fisheries experts (representing 34 nations) are consistent with the findings of the case study of CCAMLR, governed by 25 nations. Since its beginning in 1982, CCAMLR has managed to avoid collapse of the fisheries under its remit, has overseen substantial stock recovery in areas where degradation had occurred in the past and has seen through a number of continuously up-dated conservation measures with the aim of providing for marine conservation and fisheries sustainability. These activities match the measures in place for the 14 sustainable fisheries in the meta-analysis and align well with the experts' view on how to sustain fisheries. A common thread through the three analyses comprising the thesis is that abundant scientific knowledge and establishment of management programs is insufficient to ensure fishery sustainability, but that political will must match the level of management challenges to ensure sustainable marine ecosystems long term.

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Chapter 1: Sustaining fisheries and marine ecosystems

Background and challenge

Fish and fisheries provide livelihoods to millions of people around the world and contribute to the food security, economies, and well-being of coastal communities (FAO 2018). At the same time the world's seas and oceans are under increasing challenge and change. Per capita demand for seafood is rising. Fish and fishery products are highly traded commodities, adding another dimension to fisheries management. The development of globally focused industrial fisheries with highly mobile fleets has added further complicating dynamics. Nonetheless, sustaining fisheries is a key motivation for individuals, states, regional and global bodies, and a focus of effort for many years. The United Nations Food and Agriculture Organization (FAO) has long recognized unsustainable practices such as IUU fishing and overfishing causing negative ecological consequences, including reduced fish production, which in turn leads to negative social and economic consequences (FAO 2013, FAO 2018).

Apart from being a food source, the ocean is also a recreational area, a climate regulator, a transportation route and a supplier of half the planet's oxygen (Williamson et al. 2009, Branch et al. 2010, Lyons et al. 2014, Amador et al. 2016, FAO 2016). Around 60% of the world's population live within 100km of the coast; land based pollution contributes 80% of all marine pollution; 300 million people are directly dependent on fishing, and 90% of those are coastal small-scale fishers (UN 2016, FAO 2018). The many anthropogenic activities impacting the ocean and its resources, over a long period of time, have caused a number of concerns and challenges (Halpern 2008, IPCC 2011, Bergmann et al. 2015), which have led to a demand from scientists and the public in general for better management of natural resources, including fisheries (Halpern et al. 2008, Johnson et al. 2015, Bringezu et al. 2017, Schaltegger et al. 2017, Lacey et al. 2018). Relatively few studies take a holistic approach, looking across biological, environmental, governance, economic and social pressures, on how to sustain fisheries (Walters et al. 1978, Botsford et al. 1997, Begg et al. 1999, Bradshaw et al. 2000, Pikitch et al. 2004, Castilla et al. 2005, Charles 2008, Fulton et al. 2011, Fulton et al. 2014, Berkes 2015, Hilborn 2016, Bertuol-Garcia et al. 2018).

This thesis takes an interdisciplinary approach by integrating biological, environmental, governance, economic and social variables in an analysis of fisheries sustainability. A key impetus behind this research was to investigate what factors contribute to sustainable fisheries, and conversely, what factors contribute to fishery decline and collapse.

Several broad factors provide the basis for developing key variables to assess fishery sustainability and underpin sustainable fisheries management:

- Human population and demographics;
- Ecological characteristics of marine ecosystems;
- Level and type of fishing;
- Stock assessment; and
- Governance and management.

Growing population and growing demand for fish

The demand for fish products continue to rise (Merino et al. 2012, Bellmann et al. 2016, FAO 2018).This demand is driven by growing populations but also economic development and transformation such that growing middle classes in developing economies can now afford to buy more products from the ocean. Capture fisheries in marine waters reached 81.5 million tonnes in 2014, employed 56.6 million people, and engaged 4.6 million fishing vessels (FAO 2016). For developing economies, fishery exports were valued at US$80 billion in 2014, higher than other major agricultural products such as meat, tobacco, rice and sugar (FAO 2016). Fish accounts for 6-7% of all protein consumed by humans, and some 20% of the world's population depends on fish as a primary source of protein and the state of the world's fisheries can, therefore, be critical in the fight against poverty in many parts the developing world (FAO 2016). In this context, human population growth and growing competition for natural resources create additional pressures that will challenge our ability to feed the projected global population of 9.7 billion people by 2050 (FAO 2018). Healthy coastal and marine ecosystems are therefore crucial for poverty reduction, food security, and economic development worldwide.

Complexity of marine ecosystems

Marine ecosystems may be central to future food security, however they are also highly complex due to the many interacting biological and physical variables and processes (Hughes et al. 2005, Halpern et al. 2008, Mann et al. 2013). Past failure to understand those processes – and especially how they change under anthropogenic impacts – is causing major ecosystem shifts across the globe (Coleman et al. 2002, Beaugrand et al. 2008, Levin et al. 2015). For example, warming water and ocean acidification are expected to cause substantial biodiversity loss, which will reduce the resilience of ecosystems, and threaten the provision of key ecosystem services (Hoegh-Guldberg et al. 2010, Barange et al. 2014, Garcia et al. 2014). Without appropriate knowledge and understanding of how to sustainably manage ecosystems, and the human impacts upon them, the likelihood of ecological (and hence social and economic) failure is large (Lebel et al. 2006, Cvitanovic et al. 2015). Therefore, all forms of relevant information, including scientific, traditional and local knowledge, innovative and more traditional practices should be considered in setting the path towards sustainability. In short, it is clear that a whole-of-system approach to fisheries management is not only a preferred approach, but is required. The need to move to ecosystem-based fishery management is widely acknowledged (FAO 2018, Moffitt et al. 2016).

Impacts on marine fisheries

The abundance of fish stocks is subject to human impacts such as fishing (and overfishing), habitat destruction, pollutants (including urban run-off and sewage), and large scale stressors such as climate change (Dayton et al. 1995, Pachauri et al. 2014, FAO 2016, Mach 2017). Increasing evidence demonstrates synergistic impacts on fish stocks among these disturbances (Worm 2006, Diaz et al. 2008). Despite increased efforts in fisheries research and conservation, over-exploited fisheries still prevail in many regions of the world and there has been a succession of fisheries collapses that have peppered the history of commercial and advanced technology-based fishing, which has affected nearly all major fisheries regions globally. Fisheries managers and politicians are further faced with the challenge of balancing sustainable marine production and biodiversity with food security, economic considerations (e.g. wealth generation and employment opportunities) and potential political pressure. A final but perhaps obvious point is that overfishing does not only affect target species, but can represent a major threat to the whole marine environment (Pauly et al. 1998, Swartz et al. 2010, Branch et al. 2011, Worm 2016).

Over-exploited fish stocks

In a recent investigation of commercial fisheries, the Food and Agriculture Organization of the United Nations (FAO) concluded that 31.4% of fish stocks were overfished, and 58.1% of the stocks were fully fished (FAO 2016). In a study of 177 marine fish and invertebrate stocks worldwide, 63% of the stocks were found to need rebuilding or a reduction in exploitation rates to avoid overfishing and depleting the stock (Worm et al. 2009). The most extreme outcome for a fished stock is collapse, and several definitions of stock collapse have been used. In some cases it has been defined as a reduction in catch to less than 10% of the maximum historical catch, and by a long recovery period (Worm et al. 2009). However, here I classify a fishery as collapsed when a stock is down to 20% of unfished biomass levels.

It is not just the amount of fish taken out of the system that can lead to a collapse, but also how the fishing pressure affects age and size structure, as well as how fishing is distributed over time and space (Halpern et al. 2008, Pinsky et al. 2011, Rose et al. 2015). A wide variety of mechanisms, many triggered by over-exploitation, can cause a fishery to collapse, including decreased likelihood of fertilization (i.e. Allee effects), impaired group dynamics, and onset of suboptimal environmental conditions such as temperature anomalies and loss of system productivity as can be associated with ENSO events (Liermann et al. 2001, Mullon et al. 2005, Pinsky et al. 2011, Taboada et al. 2016).

Recovering fisheries

Examples of recovered fish stocks, particularly in the US, show that recovery can be slow but possible by instigating a suite of management tools such as (reduced) Total Allowable Catch (TAC), gear modification, and marine protected areas (among a range of other options), tailored to a particular fishery (Polasky et al. 2011, Costello et al. 2016). Thus, appropriate management, stewardship and governance of whole marine systems is vital for the protection of fisheries and marine biodiversity in the long term.

Governance and management

Fisheries managers are faced with the challenge of balancing sustainable marine biodiversity and production with food security, employment opportunities, other social, economic and (in some cases) legal imperatives, and potential political pressure (Rees 2017). Modern fishery governance is a systematic concept relating to the exercise of authority for managing fisheries (Kooiman 1999, Research 2005, Haward 2011, Fulton et al. 2014). Fishery governance has international, national and local dimensions (depending on the location of the fishery) and includes legally binding rules such as national policies and legislation or international treaties, as well as customary social arrangements (Gislason et al. 2000, Research 2005, Hollway et al. 2016).

Despite increased efforts in fisheries research and management there appears to still be many improvements to governance and management needed to both prevent and restore over-exploited fisheries (Gutiérrez et al. 2011, Clarke et al. 2013, Merrie et al. 2014, Barner et al. 2015). Because different exploited fish species have different life-histories, live in different types of ecosystems, and are exploited in a variety of ways by people from different cultures and social circumstances, an equally diverse range of management methods are required for sustainability (Mullon et al. 2005, Haward et al. 2008, Marchal et al. 2016).

The possibility of synergistic effects of human-induced stressors on marine ecological systems is a major consideration when assessing the health of and governing fish stocks. With increases in world population as well as higher income per capita in some highly populated countries and with more than half of global marine fish stocks already fully exploited (Bowman et al. 2007, FAO 2009, FAO 2016), it is essential to apply a holistic socioecological management approach.

Ecosystem Based Fisheries Management

The abundance of fish stocks is subject to human impacts such as overfishing, habitat destruction, pollutants, including urban run-off and sewage, and large scale stressors such as climate change and ocean acidification (IPCC 1998, Crain et al. 2008, Fulton et al. 2011, Gunderson et al. 2016). Increasing evidence demonstrates synergistic impacts on fish stocks among these stressors and disturbances, which has led to one of the fastest changes to global biodiversity in the Earth's history and has caused major biodiversity loss and ecosystem shifts (Diaz and Rosenberg 2008, Cardinale et al. 2012, Molinos et al. 2016, Pecl et al. 2017).

These well documented anthropogenic impacts on the marine environment have led to increasing calls from scientists, natural resource managers, non-governmental organisations (NGOs), and the public at large for better environmental management of marine ecosystems (Lester et al. 2010, Fulton et al. 2014). In large part these calls are the consequence of scientific research revealing the myriad ways in which fishing activities, along with terrestrial run-off, other pollution, coastal engineering, climate change, and other kinds of human-driven stressors are impacting the overall health of marine ecosystems (Pikitch et al. 2004, Rice et al. 2011, Link et al. 2017). This environmental awareness has led to consideration of so-called Ecosystem Based Fisheries Management (EBFM), or the Ecosystem

Approach to Fisheries (EAF) (Pikitch et al. 2004, Kenneth 2005, Crowder et al. 2008, Watters et al. 2013, Levin and Möllmann 2015, Nilsson et al. 2016).

The concept of the Ecosystem Approach (EA) to management has been considered for more than 30 years and has been extensively discussed, elaborated and developed within national and international fora (Browman et al. 2005, Crowder and Norse 2008, Levin and Möllmann 2015, Nilsson et al. 2016, Fernandino et al. 2018). The Convention on Biological Diversity adopted a Guidance for the Ecosystem Approach at its 5th Conference of the Parties (CBD 2000).

The ecosystem approach EBFM and EAF have been mandated and enriched in legislation in a number of nations, but it has been argued that despite committed governments, real progress to achieving EBFM and EAF has been slow (Haward 2011, Polasky et al. 2011). There are very few examples worldwide where management of fisheries has been strongly driven by considerations of ecosystem dynamics (Fulton et al. 2014, FAO 2018). One successful example, however, is the Tasmanian rock lobster fishery, where results of ecosystem models and in situ experiments focussed on multispecies interactions (among other evidence) have underpinned new management initiatives, such as introduction of spatial management, and reduced TAC across commercial and recreational sectors (Johnson et al. 2013, Johnson et al. 2015).

Challenges for fisheries management

More than half of the world's marine fish stocks are considered to be either overexploited or fully exploited with limited room for further expansion (FAO 2016). Wild fisheries production stabilised in the 1990s and demand has been met by increasing reliance on aquaculture production. The high seas, i.e. marine waters beyond national jurisdiction, covers two thirds of the ocean surface and the fishing impacts that takes place here include negative environmental impacts, such as damaging habitats, by-catch, overexploitation of migratory species, often combined with no or little management and/or compliance checks in place (Sumaila et al. 2015, Sala et al. 2018). Increasing competition between national and international fishing vessels for fisheries resources was one of the reasons behind the international negotiations in the 1970s and 1980s, leading to the adoption of the United Nations Convention on the Law of the Sea (UNCLOS) in 1982 (UN 1982, Smith 2017). China, Taiwan, Japan, South Korea, and Spain are the most active fishing nations on the high seas (Tickler et al. 2018). Although a lack of data, transparency, monitoring and compliance of the high seas make it challenging to combat negative impacts on marine ecosystems, technological developments and satellite data make it possible to obtain a more accurate picture of fishing effort and its impacts across the globe at the level of individual vessels (Kroodsma et al. 2018). There are a number of regional fisheries management organisations (RFMOs) aiming to manage a particular species, or at times several species, in a particular region of the high seas (FAO 2017). There has long been a need to further develop UNCLOS to elaborate and extend the text of an international legally binding instrument on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (ABNJ) (Druel et al. 2014). Towards this end, negotiations at an intergovernmental conference are continuing at the United Nations in New York, with the concluding session of the conference expected to be held in March 2020 (UN 2019).

Research questions

The preceding sections highlight that the problem of fisheries over-exploitation is not purely about fisheries science, but involves social and economic values and processes, and approaches to governance. Sustainable fisheries requires good understanding of the socio-economic drivers and management approaches and tools underpinning its governance as well as the ecological and environmental conditions affecting the fishery.

The overarching question addressed here is whether there are ecological, socioeconomic, or governance properties, alone or in combination, that facilitate either sustainability or increased risk of collapse in fisheries. The approach is to:

1) Identify the connections among the biological, environmental, socioeconomic, industry, governance, and management variables (individually and in combination) that affect fishery sustainability;

2) Use expert knowledge and experience to understand the main challenges in managing fisheries and ecosystems, and to identify the main tools to combat these challenges;

3) Investigate whether and how long-term practices of governance and management have, or have not, influenced the conservation status and sustainability of fisheries.

Aims and approach

The aim of this thesis is to provide insights into the structure of fisheries as socioecological systems. The project is to conduct comprehensive analyses across management, environmental, biological and socioeconomic drivers to identify the factors that contribute most to a fishery being sustainable or not. This project aims to identify and analyse factors contributing to overfishing and fishery collapse. It seeks to identify key biological, environmental, social, economic, industry, governance and management variables and associated criteria affecting the status (sustainable, depleted, collapsed) of a range of stocks. This analysis provides information on what is needed to support sustainable fisheries.

Developing variables and criteria for sustainable fisheries is challenging, and it is particularly difficult to quantify variables describing many aspects of governance, management and socioeconomic elements. As a result, qualitative indicators are commonly used in relation to governance and social goals, but qualitative indicators and objectives have further challenges to ensure that they are standardised and repeatable. Variables and criteria need to be standardised and repeatable so that two independent assessors with the same information would interpret the situation similarly. Simple standardisation and repeatability may be achieved by establishing robust indicators that are assessed in a relatively straightforward way – such as binary yes/no or positive/negative change. Using a scale of responses (high-medium-low) provides more information, while often still allowing for good standardisation and repeatability.

Where the variables and criteria are quantitative the relevant assessment can usually be defined clearly and quantitatively. If the indicator is discrete, such as the existence of a regulatory instrument or consultative body, then monitoring the presence or absence of the indicator can also provide a clear assessment. But most governance and social issues cannot be meaningfully reduced to a binary indicator and so the challenge remains to provide standardised and repeatable performance measures from qualitative data.

The variables and criteria also need to be able to be used at different scales of management – from single-species fisheries management to management of multi-species assemblages; from centralized fishery management systems to community and stakeholder led co-management approaches; and from small-scale to large-scale fisheries. Most fisheries agencies face challenges in simultaneously managing fisheries, economic development, and imperatives for social and community benefit.

The work in this thesis is intends to augment and build from those studies that have attempted to take a holistic approach in examining simultaneously biological, environmental, governance, and social pressures on fisheries (Fulton et al. 2011, Fulton et al. 2014, Berkes 2015, Hilborn 2016), often seen as supporting an ecosystem-based approach to fisheries management.

Holistic approaches to fisheries management

Work towards an integrated, interdisciplinary approach to fisheries management requires defining and explaining the main challenges of sustaining fisheries, such as uncertainty, fisheries management instruments, fisheries rights and existing obligations under the United Nations Law of the Sea Convention, the complexity of stake holder conflicts, collapse, the complexity of natural variables affecting fish stocks and fishery production, and sustainability (Smith 1986, FAO 2005, Charles 2008, FAO 2009, Stephenson et al. 2018). Much of this work has its antecedents in the late 1970s, with the introduction of ecosystem-based fisheries management under a precautionary approach into the negotiation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR 1980) (Nilsson et al. 2016).

Despite all the research and effort into developing and implementing the ecosystem approach to fisheries management there seems to be an apparent gap between science and management (Bradshaw and Borchers 2000, Bertuol-Garcia et al. 2018). Given the complex nature of fisheries and marine ecosystems and their governance, researchers are confronted with challenges in establishing metrics to adequately assess sustainability. Given the challenges in stock assessment *per se* it is not surprising that an expansion of fisheries management objectives to include, for example, considerations on the impacts of fishing on the ecosystem or socio-economic aspects of the fishery system, has made sustainability assessments and identifying the factors that contribute to both sustainability and fishery collapse difficult. Clearly science is a key here, but governance and management are also significant. For example, the reporting framework for the application of Ecologically Sustainable Development (ESD) in Australian Fisheries includes the question: 'does the fishery have sufficient management processes and arrangements in place to enable the other elements [ecological and social-economic] to achieve an adequate level of performance?' (Fletcher et al. 2000). The FAO notes that there are certain challenges to achieving sustainable fisheries, including a lack of capacity, lack of fishery data, and impacts of poverty and food security – in addition to the threats external to fishing that are common in many contexts such as loss of habitat and fishing grounds, and pollution from a wide range of human activities (FAO 2009, FAO 2013).

The thesis uses a multiple method approach, linking quantitative and qualitative research methods, in an attempt to ensure stronger and more robust analysis (Feuer et al. 2002). Feuer, Towne and Shavelson (2002) noted that it is very unlikely that any one study would possess all research qualities for a comprehensive scientific enquiry, although a successful program of research is likely to embody all of them. A clear definition of a multiple method approach is provide by Johnson et al: 'Mixed methods research is the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches (e.g., use of qualitative and quantitative viewpoints, data collection, analysis, inference techniques) for the broad purposes of breadth and depth of understanding and corroboration' (Johnson et al. 2007).

In this thesis, I include quantitative data in (1) an assessment of 21 major fisheries across the globe in which are examined key biological, environmental, social, economic, industry, governance and management variables, and (2) a global survey of 188 fisheries experts - marine scientists, managers and policy makers. Qualitative research includes analysis of fisheries management under the auspices of the Commission for the Conservation of Antarctic Marine Living Resources.

Thesis structure

Chapter 2: Fisheries sustainability relies on biological understanding, evidence-based management, and conducive industry conditions[1]

This analysis relates features of fishery governance and management to the sustainability of harvests, fishery collapse, and recovery of stocks. A survey of 21 major fisheries globally examined key biological, environmental, social, economic, industry, governance and management variables, and examined the relationship between the measures of these variables and stock collapse. I developed 51 criteria that could potentially help explain three fishery management outcomes: a stable fishery, an overfished fishery, or a collapsed fishery. The 21 diversified fisheries were selected to represent:

1. a mix of pelagic, demersal and crustacean fisheries;
2. management by developing and developed countries, as well as regional fisheries management organizations of the high seas;
3. a mix of deep sea and shallow sea fisheries; and
4. sustainable, overfished, and collapsed fisheries.

The criteria that scored highest for all the 14 sustainable fisheries were associated with elements of fish biology, the management regime, and characteristics of the industry. This analysis showed that although a fishery might have a high score for management, without a medium or high score for biological knowledge, sustainability is difficult to achieve.

Chapter 3: How to sustain fisheries: Expert knowledge from 34 nations[2]

This chapter explores expert opinion of the complexity of interactions between biological, environmental, governance, political, management and socioeconomic elements in governing marine ecosystems and fisheries. Marine governance often has to compete with socioeconomic issues such as unemployment and business models when it comes to political attention and resource allocation for management. Thus, fishery management is faced with a range of challenges, and needs to be both efficient and effective in working towards long term sustainable ecosystems and fisheries. This chapter attempts to identify the main issues with sustaining fisheries, and how to bridge the gap between scientific knowledge and governing marine systems, from the point of view of fishery management experts. An international fisheries governance survey was carried out, sampling 188 marine scientists, managers and policy makers. The intention was to gather specialist knowledge and experience from around the world in relation to marine fishery management.

The findings highlight the need for management and government to ensure close collaboration and open communication with fisheries researchers. The main challenges perceived by the fisheries experts were overfishing, habitat destruction, climate change and a lack of political will for implementation of effective and sustainable fishery

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practices. Measures to help combat these challenges included ecosystem-based fisheries management with particular attention to closures, gear restrictions, use of ITQs, and improved compliance, monitoring, and control.

Chapter 4: Consensus management in Antarctica's high seas – past success and current challenges[3]

The fourth chapter presents a case study focussing on management of Antarctic waters. The high seas surrounding Antarctica constitute a vast and diverse marine environment. Following its establishment in 1982, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has managed the ecosystems of the high seas of the Southern Ocean. CCAMLR pioneered the ecosystem approach to resource management, took action on the problem of sea bird by-catch, and has established measures to combat illegal, unreported, and unregulated (IUU) fishing. CCAMLR is often perceived as an example of best practice in managing marine resources in international waters. At the same time, CCAMLR must navigate challenges that arise in some form of balance between 'fishing' and 'conservation' interests. There are numerous cases where CCAMLR's consensus-based decision-making process has been central in shaping conservation and management outcomes, and this chapter considers these achievements and identifies emerging challenges.

Chapter 5: Conclusions - Key Lessons in Sustaining Fisheries

The final chapter integrates the three main elements of the thesis to highlight the connections among the biological, environmental, governance, management, industry, economic and social variables (either individually or in a combination) that facilitate, or hinder, fisheries sustainability. It considers this synthesis in the context of the published literature, and illuminates the limitations of the present work.

[3] This chapter has been published in *Marine Policy*: Nilsson, J.A., Fulton, E.A., Haward, M. and Johnson, C., 2016. Consensus management in Antarctica's high seas–Past success and current challenges. *Marine Policy*, *73*, pp.172-180.

Chapter 2: Fisheries sustainability relies on biological understanding, evidence-based management, and conducive industry conditions

Abstract

This paper recognises that the impacts and effects of fishing are key to marine ecosystem management and explores the relationship between fisheries exploitation and sustainable harvests, and the collapse and depletion of stocks. A survey of 21 fisheries from around the world assessed key biological, environmental, social, economic, industry, governance, and management variables and associated criteria that potentially affect stock abundance. We developed 51 criteria as potential contributing factors underpinning three main fishery management outcomes: a sustainable fishery, a depleted fishery, or a collapsed fishery. The criteria that scored highest for the 15 sustainable fisheries in the analysis were associated with the broad groupings of biology (characteristics of the species and stock), management (legal and policy frameworks, tools and decision systems), and industry (economic performance and value). This analysis showed that while a fishery might have a high score for management, sustainability is likely to be difficult to achieve without a medium or high score for biological knowledge.

Introduction

Ecosystem based management of marine systems is challenging. This is because of system complexity, a high degree of connectivity among elements, non-linear responses of these elements to environmental drivers and stressors, and difficulties associated with monitoring ocean processes. Marine ecosystems are subject to a range of anthropogenic impacts, including the impacts of fishing, which underpin rapid rates of biodiversity change and major shifts in marine ecosystems (Diaz and Rosenberg 2008, Rockström 2009, Duarte 2014, FAO 2016). Fishing has direct and indirect consequences on predator/prey relationships in an ecosystem, potentially causing cascading effects (Myers et al. 2007). Excessive fishing pressure may lead to both depleted fisheries where stocks may be overfished or, in extreme cases, collapse (with catches reduced to less than 10% of the maximum historical catch (Worm et al. 2009). This is not new phenomena as several fish stocks had collapsed by the 1930s (Jackson et al. 2001), but rapid development of large scale industrial fishing after the Second World War has hastened exploitation of global fisheries (Myers et al. 2003). In the past decade a number of analyses have shown that approximately a third of the world's exploited fish stocks are depleted to unsustainable biomass levels (i.e. overfished) (Worm et al. 2009, Costello et al. 2012, FAO 2016). These studies show that on-going policy commitments and management efforts are required in national and international waters to secure sustainable harvest of marine fisheries into the future.

Considerable attention has been given to tools and approaches that will predict at which abundance level a fish stock is threatened by collapse or extinction (Myers et al. 1995, Cook et al. 1997, Carlton et al. 1999, Halpern 2008, Hutchings et al. 2010). Studies of stock recovery show that reversal of a long-term decline in fish abundance is typically a slow process, with rate of recovery dependent on many factors, especially life history – such as the age of maturity (Hutchings et al. 2004, Hutchings 2005). The long time frames involved create additional cognitive and political challenges for managers struggling with recovery of depleted stocks (Costello et al. 2016). A key question is, therefore; given the effort directed at fisheries management, why is it that so many fisheries are collapsed or overfished?

This paper accepts the premise that understanding the impacts and effects of fishing are key to sustainable marine resource management and the sustainability of marine ecosystems (Pauly et al. 1998, Moffitt et al. 2016, Walters et al. 2016, Melnychuk et al. 2017). Here we explore 21 commercial fisheries and explore the relationship between fisheries exploitation and sustainable harvests, and the collapse and recovery of stocks. We accept that the focus on a set of data-rich commercial fisheries is a potential limitation, but consider that it is an acceptable compromise since analysis of data-rich fisheries enables identifying the key factors affecting the sustainability of stocks.

Methods and background

General study design

Studies of the world's fisheries are only possible where data are freely available, noting that existing data may be incomplete (e.g. it may exclude by-catch and discards). Patchiness in available data has constrained status assessments for many fisheries around the globe. Moreover, most published studies that do try to assess the global status of fisheries do not consider or integrate ecological, legal, regulation, economic, and social aspects. Few have attempted to identify specific sets of characteristics that distinguish sustainable fisheries from those that have collapsed. Nor have they identified criteria that may indicate, *a priori,* fisheries that are prone to collapse. Here we aim to do just that - to identify the multidisciplinary set of variables and criteria, alone or in combination, that indicate whether a fishery is likely to be sustainable, depleted, or collapsed.

We assigned fisheries status based on definitions established for this exercise rather than relying on national assessments and definitions that often differ from fishery to fishery. For the purposes of this study the following definitions are used:

- A *sustainable* fishery is where fishing pressure is at or less than F-targ and the stock size is around its target reference point level, i.e. long-term depletion due to overfishing has either not occurred or the stock has fully recovered from past excessive exploitation.
- A fishery was categorised as *depleted* when the stock had dropped below the target reference point (F-targ) for the fishery, which is typically set or assumed to be maximum sustainable yield (MSY). We appreciate that stocks may dip into this zone via environmental variation, but in the main species considered here were in this state due to prolonged overfishing (excessive fishing pressure leading to depletion of the stock) and so the term is appropriate as a shorthand reference.
- A fishery was categorised as *collapsed* when the stock(s) had been fished until the biomass was depleted to <20% of unfished biomass levels, which is taken as the proxy limit reference point for stocks in Australia; beyond this point no targeted fishing pressure should be applied.

While we acknowledge that stock status is a continuum, it is standard fisheries practice to classify stocks into a few small classes – such as sustainable or over exploited. The general concept of these classes is similar across jurisdictions, however, the devil is in the detail – with explicit definitions differing between countries (for example). Consequently, we assigned fisheries status based on definitions established for this exercise rather than relying on national assessments and definitions that often differed from fishery to fishery.

The selected six variables and their 51 associated criteria (Table 1, Supplementary material 1, 2) have individually been considered in detail by a large number of researchers around the world, and introduced and evaluated in peer reviewed scientific journals over the past four decades. Multidisciplinary synthesis using subsets of these criteria have been rare, but it is necessary to bring the complete suite together to understand the highly complex nature of fisheries science and management. This is because understanding the interrelations amongst the six classes of variables and their criteria is likely to be key to appreciating the full complexity of marine systems, the fisheries they support, and means of governance and management that achieve sustainably. The variables are explained in detail in Table 1. The reference time period for the study was 2011-2016 (Supplementary material 2 and 3).

Table 1: Key variables and scoring used for the analysis of fisheries.

	Criteria	Score 2	Score 1	Score 0
Variable 1 – Biology				
A core challenge in fisheries management is defining which ecological indicators to use when estimating a stock's carrying capacity, so that long-term sustainable catch limits can be set in an ecosystem-based context (Fulton et al. 2005, Welsford 2011, FAO 2016, Melnychuk et al. 2017). Understanding and modelling stock abundance and the many variables affecting this abundance, such as food-web relationships, habitat, birth, death and migration, including age / size structure is clearly a demanding task (Schaefer 1954, Wilderbuer et al. 1999, Fulton et al. 2014, Fulton et al. 2016). A wide variety of mechanisms, many triggered by over-exploitation and reduced adult body size, can cause a fishery to collapse, including decreased fertilization probabilities, habitat destruction, impaired group dynamics, and environmental conditions such as temperature and ENSO events **(Liermann and Hilborn 2001, Mullon et al. 2005, Audzijonyte et al. 2015)**. Moreover, fishing pressure and how it is distributed over time and space also plays a significant impact on fish abundance (Halpern et al. 2008). Several studies suggest that when fishing pressure is reduced stocks almost always increase in abundance, although some stocks take many years, proving fishing mortality is key to stock recovery (Barner et al. 2015). This could, however, be because there were no significant environmental changes to those systems. Given the increased stress from climate change and ocean acidification, decreasing fishing mortality alone may not be sufficient for recovering a stock (IPCC 2011, Kawaguchi et al. 2011, Kroeker et al. 2013, Hilborn et al. 2014, Frommel et al. 2016).	Breeding	fast growing/early breeders	slow growing/late breeders	-
	Migratory	no/little migration	migratory	-
	Fecundity	high recruitment	low recruitment	-
	Diet specialisation	no special diet	special diet	-
	Age / size distribution	viable age/size distribution for sustainable stock; distribution that is healthy and can remain productive	no viable age/size distribution for sustainable stock	-
	Habitat specialisation of life stages	Particular habitat specialisation during some life stages	no habitat specialisation	-
	Spatial connectivity	larvae dispersal	no/low larvae dispersal	-
Variable 2 – Environment				
During the last 40 years much effort has been spent on trying to understand all the biophysical processes involved in the marine world, including physics, connectivity, chemistry, habitat, networks, recruitment and interactions of prey and predators in food webs (Young et al. 2007, Rockström et al. 2009). Apart from anthropogenic pressures, natural variability such as oceanographic drivers of oxygen and salinity levels also have an effect on biological processes including food supply, reproduction, fecundity, connectivity and survival rates (Cury et al. 2008).	Ocean Health Index	healthy (90 and above)	medium health (80-89)	low health (<80)
	Clean Waters (OHI)	low contaminated (>90)	medium contaminated (80-89)	high contamination (<80)
	Carbon storage	>80	60-80	<60
	Anthropogenic influence on habitat (fishing, pollution)	low/absent	high	very high

Failure to understand processes and relationships has been seen to cause major ecosystem shifts in food webs **(Hughes et al. 2005, Crowder and Norse 2008, Curtin et al. 2010, Fulton 2016)**. Human actions effecting the climate and biosphere have the potential of significantly affecting many critical marine ecosystem services, in particular biodiversity and food security (Fulton et al. 2011). In turn, biodiversity loss is likely to decrease the ability of ecosystems to resist the effects of climate change, possibly also affecting the climate system itself (Cardinale et al. 2012).	Disease / virus / toxic algae blooms / invading spp	Little	high	very high
	Acidification	no effect (fish)	effect (calcification, crustaceans, mainly)	-
	Hot spot area (climate change	no hotspot area	hotspot area	-
	Climate variability	no regular impact	some impact	regular impact
Variable 3 - Social and economic				
One universal dilemma is the increasing size of the human population and the way we need to feed more than 9 billion people by 2050 (FAO 2016). Around 60% of the world's population live within 100km of the coast; land based pollution contributes 80% of all marine pollution; 300 million people are directly dependant on fishing, and 90% of those are coastal small-scale fishers (FAO 2016, UN 2016). In 2014 global capture from marine waters was 81.5 million tonnes with a global fishing fleet of 4.6 million vessels (FAO 2016). The cultural and well-being aspects of the loss from ecosystem services are also drivers in the challenge of conserving nature (McCauley 2006).	Human Development Index (HDI)	developed nations 0.75-0.9	developing nations 0.74-0.5)	underdeveloped nations <0.4)
	Coastal Livelihoods & Economies (from OHI)	increased economics	no economic development	decreased economic development, or no info
	Poverty and Economic Decline Index	low decline (<1.6)	medium decline (1.7-5.5)	high decline (>5.5)
	Education Index	>.9	<.9	<.8
	Community involvement	High	low	none
	Artisanal fishing (OHI)	high access	low access to fishing	very low access to fishing
	Vital protein source	Low	medium	high
Variable 4 – Industry				
Small-scale fisheries employ more than 90% of the world's 36 million fishers **(FAO 2018)**.The annual value of fish products is estimated to about $US94 billion **(FAO 2016)**. However, a study by the World Bank and FAO (2008) showed that the world's fishing fleets have an annual economic loss of some US$50 billion, calculated as the difference between the potential and the actual net economic benefits due to government subsidies and over-exploited fish stocks**(FAO et al. 2008)**.There are many	Subsidies (case by case evaluation)	positive for regulated countries	-	negative for unregulated fisheries,
	Commercial value	low risk of IUU fishing	medium risk of IUU fishing	high risk of IUU fishing

examples of how fisheries operators influence conservation in a positive way (Brewer et al. 2015).	Paid quota or membership fee	yes, low fee	-	no / no info found
Variable 5 – Governance				
The type of governance, including corruption and state legitimacy, plays a vital role on how effective management and conservation measures will be to sustain, in this case, a natural resource such as fisheries (Provan et al. 2008).	Global Peace Index (GPI)	high peace (light yellow)	medium peace (yellow/orange)	low peace (red/yellow/brow n)
	Gini Index	high equality	medium inequality	high inequality
	Fragile State Index	Sustainable	stable	alert/warning
	Anti-corruption Perceptions Index (where more than one country was involved in management, the average score was used)	low corruption (yellow)	medium corruption (orange)	high corruption (red)
	State Legitimacy	good (<1.7)	weak (1.8-4.9)	poor (>5)
Variable 6 – Management				
Managing cumulative anthropogenic pressures on marine ecosystems is a challenge (Halpern et al. 2008). Given that there are many environmental, biological and socioeconomic variables affecting the over-all health of the oceans, decision makers have frequently been asking if there is enough scientific information and knowledge of ecological functions and processes to implement an ecosystem approach to marine and fisheries management (Lester et al. 2010). Ecosystem-based fisheries management include a range of tools, including Marine Protected Areas, Individual Transferable Quotas and co-management (Smith et al. 2007, Marshall et al. 2018). However, without appropriate knowledge and understanding of how to design multi-species and multi-annual fishing plans and how ecosystems supporting fisheries and the communities the fisheries are imbedded in, it is unlikely that management will succeed (Fulton et al. 2011). Even though there are many ecological processes to understand further, it is widely recognised that we do have a significant amount of scientific information to start implementing Ecosystem-based Management all around the world (Tallis et al. 2010, McLeod et al. 2011).	Fisheries legal framework	Yes	some	no
	Management agency	Yes	-	no
	Overall food provision	sustainable (>80)	overexploited/rebuilding (21-79)	high risk of collapsing (<20) or no info
	Life history known	high knowledge	low knowledge	no knowledge
	Stakeholder involvement	yes	little	no
	Stock quota	Yes	-	no
	Property rights	Yes	partly	no
	Catch/gear restrictions	Yes	-	no

	Seasonal closures	Yes	Planned	no
	Spatial management	Yes	in the process	no/no info
	Monitoring Compliance System	Yes	Some, in the process	no plan/program/info
	Certification	MSC/MBA cert	other certification	no certification
	Science-based decision making	yes	mentions it/somewhat	no
	Food web knowledge	Yes	some	no
	Breeding/size protection	protection (area or spp)	some protection	no protection
	Capacity building	Yes	little	no info
	By-catch / mortality management (incl. IUU fishing)	management in place / part of quota	some	no
	Stock assessments	population dynamics model	catch rate vs historical model	none
	Stock survey	scientifically collected	catch base	no survey
	EBFM	Yes	-	no
	Vessel Monitoring System	Yes	some	no

In addition to the data collection, an 'expert elicitation' approach was used as a method of verification of each case study (discussed further below). After the project team had scored the fisheries based on publicly available information and the criteria outlined in Table 1, experts on each fishery were approached to check the ratings or to highlight where these may be in error and require correction. Experts are defined as people with broad expertise and skills in analytical judgement together with essential knowledge of a given subject (Burgman et al. 2011). This method has been widely used to collect data in the natural and social sciences (Lenton et al. 2008, Choy et al. 2009). In this research, we called upon stock assessment scientists and fisheries managers who had close involvement in and/or knowledge of a fishery. Each of the experts have at least a masters degree in marine science and have been working with the specific fishery for a minimum of four years. At least one expert per fishery was engaged and these experts commented on each of the six variables and the 51 criteria. A glossary of terms was provided to ensure all criteria were understood (Table 1). The identity of the experts is confidential (as required by the ethics rules under which the work was conducted).

Scoring criteria

A mixed method research approach was used to better understand the complexity of sustainable, depleted, and collapsed fisheries. A qualitative scaling method was used when evaluating the status of each criterion for each case study location, *viz.* 2=potential positive impact on the fish stock, 1=potentially some positive impact on the stock, 0=potential negative impact on the stock. Note also that where no or insufficient data were available, a criterion was scored as zero on the basis of applying a precautionary approach. In the relevant supplementary material, criteria scored as '0' for reasons of no or insufficient data are indicated, and represent only 8% of cases with a zero score. Given there were a different number of criteria for each variable, aggregate scores were created for each variable (via simple addition of the criteria scores) and then rescaled so that all the aggregate indices were scored on a scale of 1-5. This meant that to achieve a score of 5 in this final rescaling the variable had to score at the maximum level for all criteria during the initial scoring (i.e. each criterion had to receive a 2 in the initial impact ranking). The aggregate scores for the variables were summed to give an overall score per fishery. There was no differential weighting across the variables.

We acknowledge that bias may be introduced by having a different number of criteria per variable and by applying equal weighting across all variables. Given the available data such an approach is valid, robust, and defensible.

Due to the challenges associated with drawing together such broad ranging information, a case-study approach was used for this investigation so that concepts might be developed and generalisations identified from which could be developed a framework for future broader application (Evans 2002, Dixon-Woods et al. 2005, Jabareen 2009). Thirty-two fisheries world-wide were investigated initially, and twenty-one of those were judged to have sufficient data available for our analysis while also representing a diverse set of fisheries types. The fisheries chosen represent pelagic, demersal, and crustacean fisheries; are managed by developing and developed countries as well as by regional fisheries management organizations of the high seas; are a mix of deep sea and shallow sea fisheries; and represent sustainable, depleted and collapsed fisheries (at the time of data collection, 15 fisheries were categorised as sustainable, 1 was depleted and 5 were collapsed).

Where multiple stocks are considered within one fishery (for example each of the cod fisheries listed is considered to have multiple constituent stocks), the fishery was classified based on the status of the majority of stocks. While at least 1 of the 5 orange roughy stocks recognised in Australia was not considered as heavily depleted, the majority of the entire fishery was classified as collapsed. These fisheries level classifications were checked with experts on each fishery (as detailed further below).

Methods and results

Methods

Multivariate analyses were used to identify similarities and differences among the different fishery sustainability categories and, in particular, to identify those variables that most clearly differentiate among fisheries classified as sustainable, depleted, or collapsed. We compared results of multidimensional scaling (MDS) (Young 2013), an unconstrained ordination, and a canonical analysis of principal co-ordinates (CAP) (Anderson et al. 2003), an ordination constrained by the *a priori* classification of fisheries as sustainable, depleted or collapsed. MDS, CAP and radar charts were used to display groupings and ratings among the fisheries, variables and criteria. MDS and CAP were undertaken using the PRIMER6 package with the PERMANOVA+ addon (Anderson et al. 2008). It is useful to compare MDS and CAP ordinations of the same data since the degree of (dis)similarity in the two ordinations provides useful information of the relative magnitude of within- and between-group variability, i.e. it is more informative to run both analyses than either one on their own.

Analysis included investigating all variables, all criteria and all fisheries simultaneously, and then looking at each of the variables and their associated criteria separately. The radar charts showed the individual score per variable, and a holistic overview of the contributions across the six different variables per fishery.

Results

Table 2: Assessment of fisheries indicated by the aggregate scores for each of the six variables (B=biology, E=Environment, SE=socioeconomic, I=industry, G=governance, M=management). The maximum possible score for each variable was 5 (indicating desirable attributes) and thus the maximum possible overall score per fishery was 30. The fisheries are presented from highest to lowest total score. High scores indicate features deemed ‘positive’ for the fishery, while low scores indicate a ‘negative’ attribute.

Scale: 1-5 (1=poor, 5=excellent)

Fisheries	**B**	**E**	**SE**	**I**	**G**	**M**	**TOT**
Northern Prawn Fishery (*Fenneropenaeus merguiensis. Fenneropenaeus indicus, Penaeus esculentus, Penaeus semisulcatus, Metapenaeus endeavouri, Metapenaeus ensis*), sustainable (Northern Australia)	4.6	4.1	3.9	4.2	3.5	4.8	25.1
Rock lobster (*Panulirus cygnus*), sustainable*1 (Western Australia)	4.6	3.4	3.6	5.0	3.5	4.6	24.7
Herring (*Clupea harengus*), sustainable (Iceland)	3.9	4.1	3.6	5.0	3.0	4.8	24.3

Patagonian toothfish (*Dissostichus eleginoides*), sustainable (Macquarie Island, Australia)	4.6	4.1	2.9	4.2	3.5	4.9	24.1
Rock lobster (*Jasus edwardsii*), sustainable (Tasmania, Australia)	4.6	3.1	4.3	4.2	3.5	4.0	23.7
Cod (*Gadus morhua*), collapsed (Atlantic Ocean, Canada)	3.6	3.1	4.6	3.3	4.0	4.6	23.3
Cod (*Gadus morhua*), sustainable (Iceland)	3.9	3.1	3.6	4.2	3.5	4.6	22.9
Cod (*Gadus morhua*), sustainable (Barents Sea, Norway/Russia)	3.9	3.1	4.3	4.2	2.0	5.0	22.5
Alaska Pollock (*Gadus chalcogrammus*), sustainable (Alaska, USA)	4.3	3.8	3.6	4.2	2.0	4.5	22.3
Cod (*Gadus morhua*), sustainable (EU, Baltic Sea)*2	3.9	3.4	3.6	1.7	4.5	4.5	21.6
Patagonian toothfish (*Dissostichus eleginoides*), sustainable (South Georgia Islands, UK)	3.9	2.8	1.8	4.2	4.0	4.8	21.5
Orange Roughy (*Hoplostethus atlanticus*), collapsed (Tasmania, Australia)	2.5	3.8	3.6	3.3	3.5	4.5	21.2
Southern Bluefin Tuna (*Thunnus maccoyii*), collapsed (CCSBT, high seas)	3.6	3.1	3.6	2.5	3.0	3.7	19.5
Hake (*Merluccius paradoxus*), sustainable (South Africa)	3.2	3.8	1.8	5.0	1.0	4.2	18.9
Anchoveta (*Engraulis ringens*), sustainable (Peru)	5.0	2.2	2.1	4.2	0.5	3.7	17.7
Hake (*Merluccius gayi peruanus*), sustainable (Peru)	3.9	2.5	2.5	4.2	0.5	3.8	17.4
Antarctic and Patagonian Toothfish (*Dissostichus mawsoni and Dissostichus eleginoides*), sustainable (CCAMLR, Ross Sea, high seas)	3.9	4.4	1.4	3.3	0.0	4.0	17.1
Atlantic seabob (*Xiphopenaeus kroyeri*), sustainable (Suriname)	3.6	3.4	2.1	3.3	0.5	4.2	17.1
Sardines (*Sardinops sagax*), collapsed (Namibia)-	3.2	2.2	1.8	3.3	1.5	4.0	16.1
Patagonian toothfish (*Dissostichus eleginoides*), depleted (Prince Edward Island, South Africa)	3.6	3.8	0.0	3.3	0.5	4.0	15.2
Eel (*Anguilla anguilla*), collapsed (EU, high seas)	2.9	3.1	2.5	1.7	2.5	2.5	15.1

*1 This stock is considered sustainable despite an extended period of low puerulus settlement, as this climate-driven phenomenon was compensated for by significant effort reductions designed to increase residual stock abundance (de Lestang et al. 2014).

**2* At the time of data collection, the Baltic cod fishery was MSC certified, and based on the overall information available at the time it was classed as a sustainable fishery. In December 2015, however, the fishery lost its MSC Certification. As stock assessment data are uncertain it may now have a different classification.

The three categories of fisheries (sustainable, depleted and collapsed) were all found to have scores for individual criteria that ranged from low to high (Table 2), i.e. no fishery demonstrated uniformly high or low scores across all variables. For example, the sustainable Peruvian anchoveta fishery had the highest score for 'biology' (5), but a low score for 'environment' (2.2), and a very low score for 'governance' (0.5). The collapsed orange roughy stocks in Australia had the lowest 'biology' score (2.5), but a high 'management' score (4.5). For the total score (a maximum possible of 30), the sustainable Australian Northern prawn and WA rock lobster fisheries scored the highest (25.1 and 24.7), while the collapsed EU eel fishery and depleted Patagonian toothfish in South Africa scored the lowest (15.1 and 15.2).

There was no difference between developing and developed countries with regards to the presence of sustainable *versus* depleted/collapsed fisheries, suggesting that for long-term commercial fisheries there are criteria other than governance alone that influence the sustainability of fished stocks. The three fisheries that received the lowest scores (South African Patagonian toothfish, EU eel, and Namibian sardines) were defined as collapsed or depleted. However, the absolute score is not a reliable indicator of fishery sustainability by itself, as a number of 'sustainable' fisheries had a relatively low overall score.

All the depleted and collapsed fisheries were associated with a medium to high risk of IUU fishing, while for sustainable fisheries the risk of IUU was low to medium. A high score (i.e. 2 in the initial scoring) for the anti-corruption criteria meant that the government structure and management is perceived as open and transparent, which may help combat IUU fishing and corruption. While a high score (2) for this anti-corruption criterion is not a guarantee of no corruption, it does indicate the existence of regulatory measures that make it more difficult to perform illegal or unethical actions.

Multivariate Analyses

While the MDS did produce a tight cluster of fisheries (in which the majority but not all were those classed sustainable), with a halo of other fisheries, there was no simple pattern based on taxa, fishery status or geographic region. While some claim can be made that Southern hemisphere stocks (anchoveta, seabob, southern bluefin tuna, hake and some toothfish) sit separate to northern stocks this is not true for all as the orange roughy, northern prawn and some of the toothfish fisheries sit in amongst the tightly clustered group (Fig. 1, bottom left). Similarly, while there appears to be some separation between toothfish and forage fish (sardine, hake and anchoveta) fisheries, again the demarcation is not unequivocal as herring and other toothfish again sit in the tight central clump (Fig. 1). Likewise, while the majority of the tightly clustered fisheries (bottom-left, Fig. 1) are marked as sustainable (Alaska Pollock, cod EU, cod Iceland, cod Norway/Russia, herring, Northern Prawn Fishery, Australian toothfish, South Georgia toothfish, rock lobster WA), two are collapsed (cod in Canada, orange roughy). The tight cluster represents fisheries with high aggregate scores for the 21 management criteria (Fig. 1; Fig. 3a,d, i, j, l, m; Fig. 4b, e). The collapsed eel and southern bluefin tuna fisheries stand out from all others, with a low overall score, particularly for industry, governance and management (Fig. 1, Fig. 5c,d).

In contrast, the CAP analysis showed a clear separation of stock categories, particularly of collapsed/depleted versus sustainable fisheries (Fig. 2). The distinct differences in the two ordinations of the same dataset indicates that that variation across characteristics of fisheries within a stock status category is large relative to differences in the characteristics of the fisheries between the different stock sustainability categories. Thus, in the unconstrained MDS ordination, separation of fisheries only weakly aligns with stock status (Fig. 1). In contrast, when fishery status categories are defined and the CAP ordination constrained accordingly (i.e. to maximally differentiate between status categories relative to variation within categories), the different stock categories become more distinct, particularly in the separation of collapsed/depleted fisheries from sustainable fisheries (Fig. 2). Thus, the vector overlay enables unambiguous identification of the criteria that best align with the distinction between collapsed/depleted and sustainable fisheries.

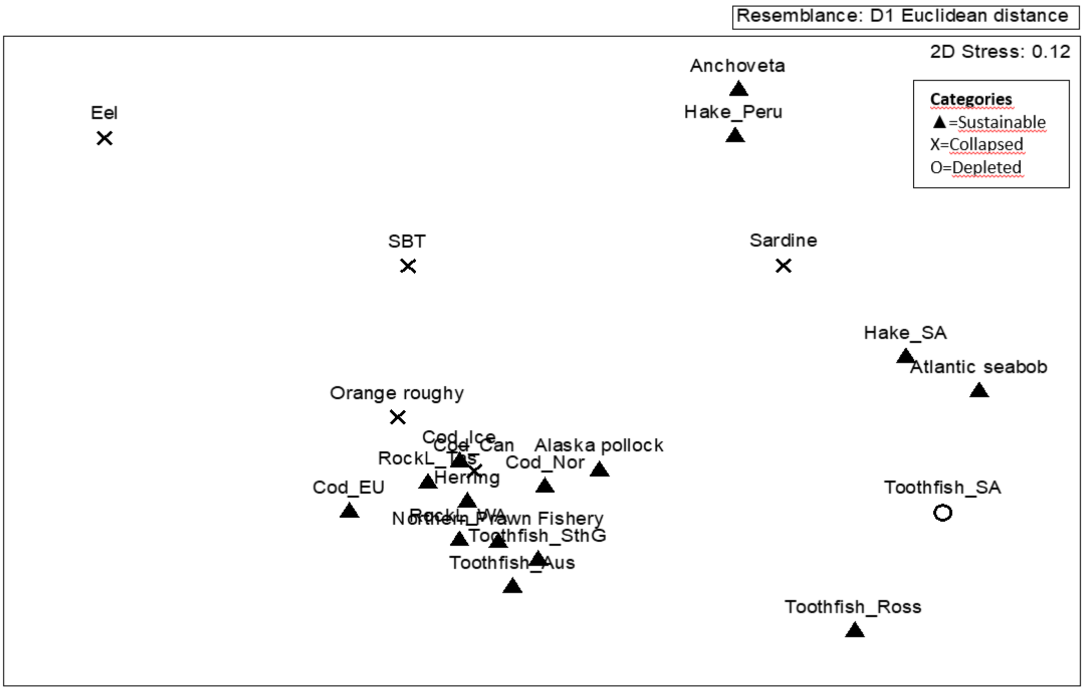


Figure 1: Multidimensional scaling (MDS) plot indicating the target taxa and status of the different fisheries (S=sustainable, C=collapsed and D=depleted).

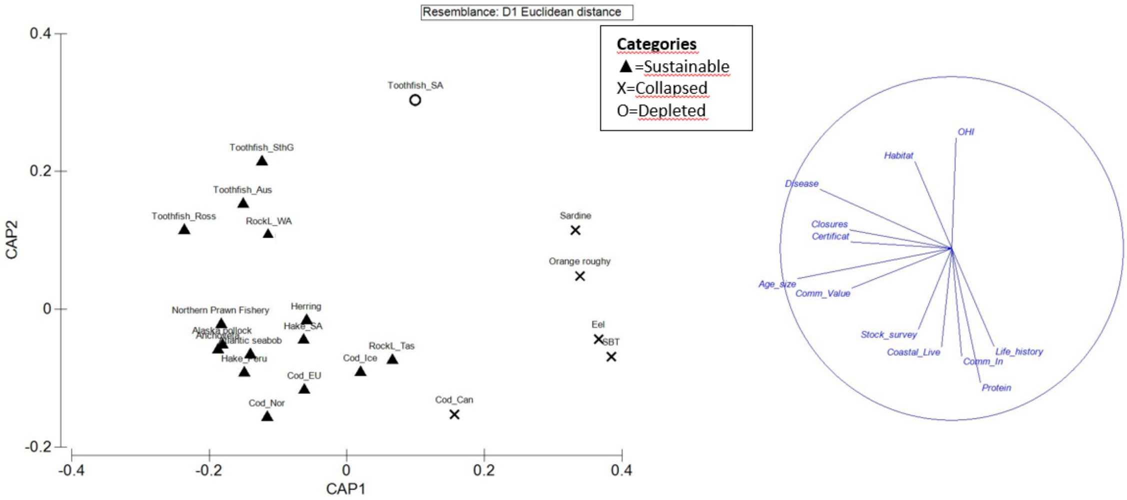


Figure 2: Canonical Analysis of Principal coordinates (CAP) showing a clear separation between collapsed and sustainable fisheries (S=sustainable, D=depleted and C=collapsed). The analysis is based on *m* = 7 PCO axes which explained 75.7% of the total variation, and 71.4% of samples were allocated to the correct group (S=sustainable, C=collapsed and D=depleted).

For the CAP analysis, the first two canonical correlations are $\delta 1 = 0.91$ and $\delta 2 = 0.55$, indicating clearly that CAP1 is most strongly associated with group differences, consistent with the ordination which shows clear separation of 'sustainable' and 'collapsed' stock on the first CAP axis (Fig. 2). By considering the vector overlay associated with the CAP analysis, it is possible to identify the key criteria that best discriminate between sustainable and unsustainable fisheries (at least in terms of realised stock status), namely disease, closures, certificate, Age_Size and Comm_Value. This means that sustainable fisheries had certification, a commercial value that prompted efforts in management, little or no disease present, management tools in place (such as MPAs or seasonal closures, TAC, and size and gear restrictions), and they had a size/age distribution amenable to sustaining a future stock. Increasing values of all these criteria align with the sustainable fisheries.

Sustainable fisheries

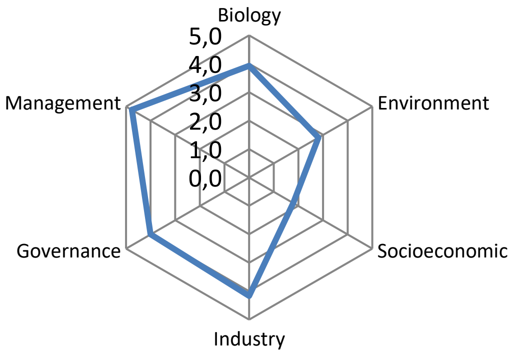
For the sustainable fisheries, the overall score ranged between 25.1 and 17.1. The 15 sustainable stocks had an average score of 4.1 for biology, 3.4 for environment, 3.0 for socioeconomic, 4.1 for industry, 2.4 for governance, and 4.4 for management. All sustainable fisheries scored above 4 on biology, management, and industry criteria. This means that the sustainable fisheries scored highly with regards to the several criteria associated with each of these three variables. For example, all sustainable fisheries scored 2 (out of a maximum possible 2) for information on viable age/size distribution (making it possible to sustain the stock), while none of the collapsed/depleted fisheries did.

The fishery that reached the highest overall score was the Australian Northern Prawn Fishery (total score = 25.1). It scored very highly on biology, environment, industry and management, and high on socioeconomic criteria (Fig. 3l). The WA rock lobster had the second highest score (total score was 24,7) (3b). Iceland also manages a sustainable cod fishery, which had high scores for industry and management criteria with an overall score of 24.3 (Fig. 3g). Equally high was the sustainable cod fishery in the Barents Sea, jointly managed by Norway and Russia, with high scores for industry, socioeconomic and management criteria, and with an overall score of 23.0 (Fig. 3i). The cod fishery in the Baltic Sea (at the time assessed as sustainable by MSC) had an overall score of 21.4 (Fig. 3m). In December 2015, however, the Baltic cod fishery lost its MSC certification. Although this fishery scored very high for governance and management, it scored low for industry (no paid quota, and low commercial value), and attained only moderate scores for environment (very low score on the Ocean Health Index, high anthropogenic influence on habitat, and high climate variability) and socioeconomic criteria. This fishery would be currently classified as depleted as the stock does not have a viable age/size distribution.

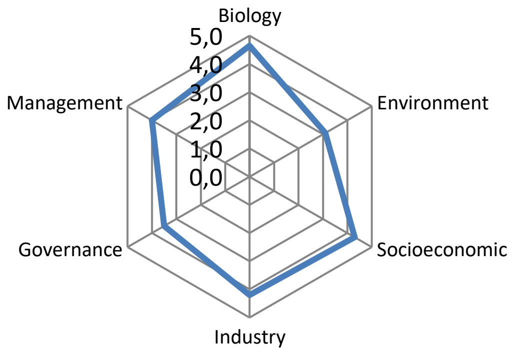
The four toothfish fisheries we analysed are governed by four different nations/organisations, and three of the four were deemed sustainable. Overall, toothfish fisheries separate from the other sustainable fisheries in having high scores for Ocean Health Index (OHI), closure, certification, disease and habitat, and low scores for breeding, stock survey, Gini index, protein source and community involvement. The depleted South African toothfish fishery differs from the three sustainable ones, mostly with regards to knowledge of stock age and size distribution, commercial value, and to a lesser extent closure and the absence of fishing certification. The sustainable Australian MSC certified Patagonian toothfish fishery around Macquarie Island scored very highly for biology and management, and high for governance, with an overall score of 24.1 (Fig. 3d). The Antarctic toothfish fishery in the Ross Sea, also sustainable, scored high for environment and management criteria but had an overall score of only 17.1 reflecting a low score for governance (Fig. 3c), as did the depleted fishery managed by South Africa (Fig. 4f). The British Patagonian toothfish fishery around South Georgia scored very high for management, governance, and industry criteria with an overall score was 21.5 (Fig. 3a). The risk of corruption, and thereby not complying with the conservation measures in place, seems to be the factor separating these four fisheries.

Among the sustainable fisheries, scores varied widely for the governance criteria, ranging from 4.5 for the Baltic cod to 0.5 for the hake and anchoveta fisheries in Peru. The sustainable fisheries also demonstrated a large range of scores on social and economic criteria, with the cod fishery in the Barents Sea and the rock lobster fishery in Tasmania scoring the highest (4.3) and the Antarctic and Patagonian toothfish fisheries in the Ross Sea scoring the lowest (1.4). While the sustainable Tasmanian rock lobster fishery and the sustainable Barents Sea cod fishery both scored very highly (4.3) on social and economic criteria, so did the collapsed Canadian cod fishery (4.6). The Western Australian rock lobster fishery had the second highest score of all fisheries surveyed (24.7), with particularly high scores for biology (4.6), industry (5.0) and management (4.6) (Fig. 3o).

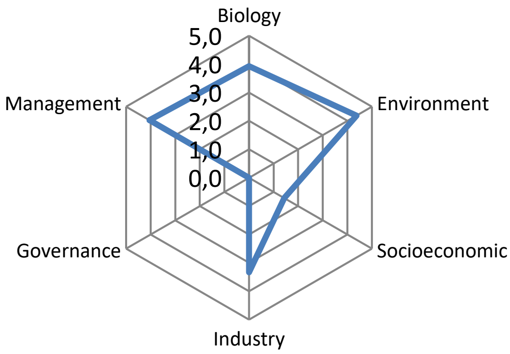
(a) Patagonian toothfish (South Georgia, UK), Sustainable



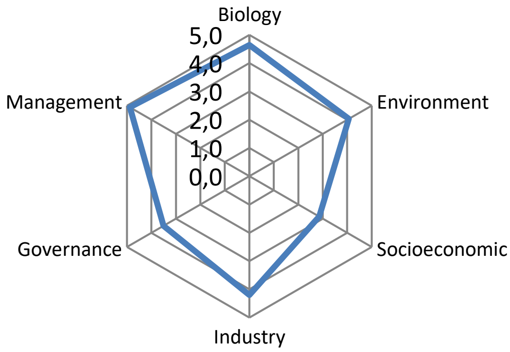
(b) Rock lobster (Tasman Sea, Australia), Sustainable



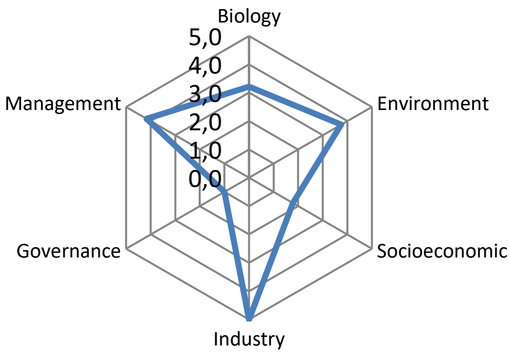
(c) Antarctic toothfish (Ross Sea, high seas), Sustainable



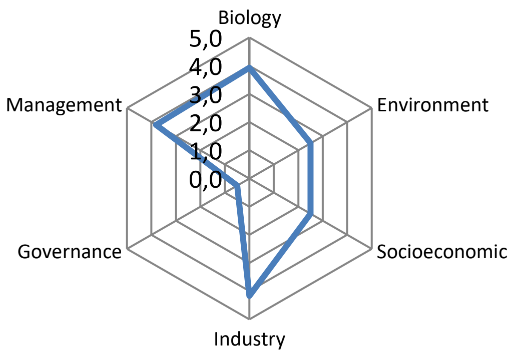
(d) Patagonian toothfish (Macquarie Island, Australia), Sustainable



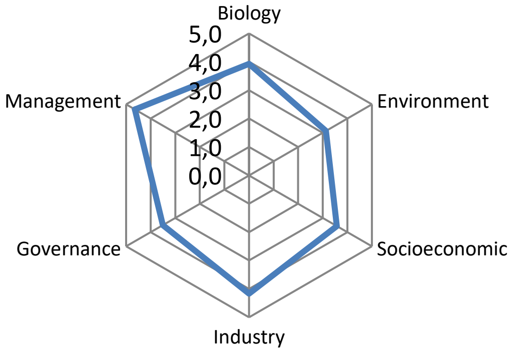
(e) Hake (Benguela Current, South Africa), Sustainable



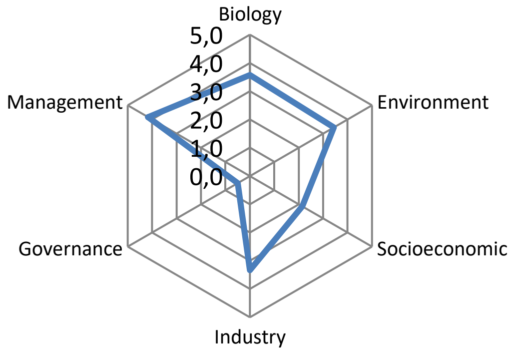
(f) Hake (Humbolt, Peru), Sustainable



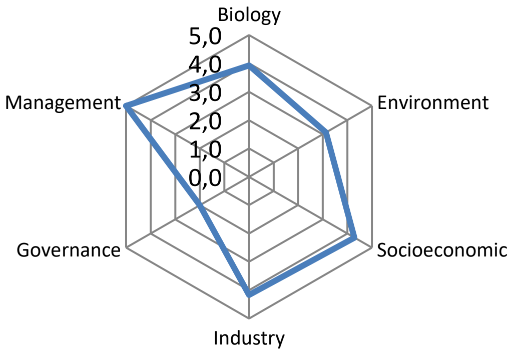
(g) Cod (Norwegian Sea, Iceland), Sustainable



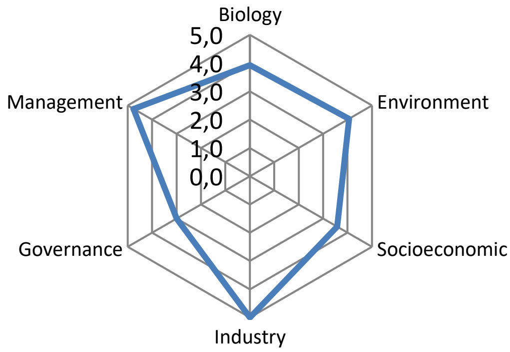
(h) Atlantic seabob (Surinme), Sustainable



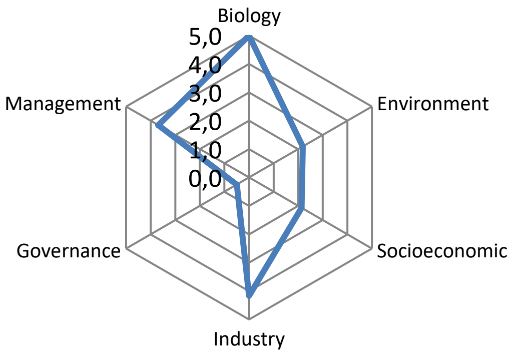
(i) Cod (Barents Sea, Norway/Russia), Sustainable



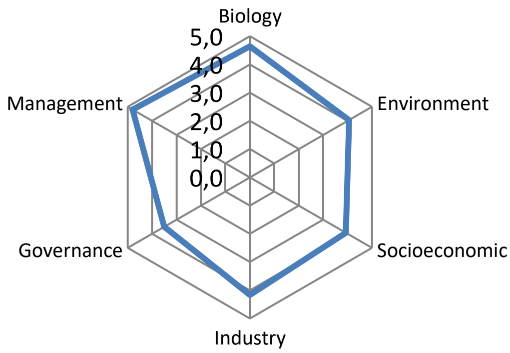
(j) Herring (Norwegian Sea, Iceland), Sustainable



(k) Anchoveta (Humbolt, Peru), Sustainable



(l) Northern Prawn Fishery (Coral Sea, Australia), Sustainable



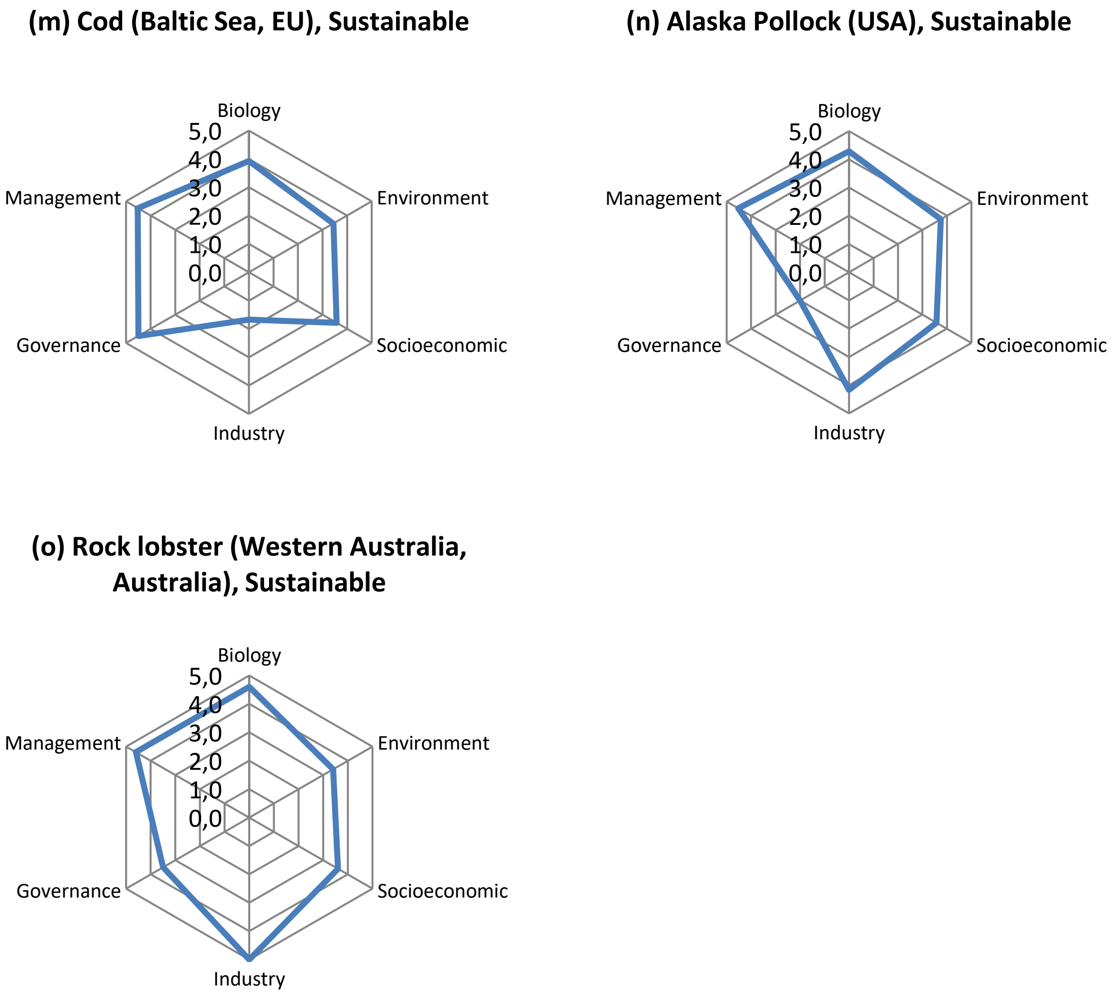


Figure 3a-o: Average scores across the six variables for each of the fisheries rated as sustainable at the time of data collection.

Depleted and collapsed fisheries

Total scores for the six depleted/collapsed fisheries also spanned a wide range, between 23.3 (Newfoundland cod fishery) and 15.1 for the collapsed EU eel fishery. The collapsed and depleted fisheries had an average score of 3.2 for biology and environment, 2.7 for socioeconomic, 2.7 for industry, 2.9 for governance, and 3.9 for management – lower scores overall in all of these areas than for the sustainable fisheries (Fig. 4a-f).

All but one (orange roughy) of the collapsed fisheries are for migratory species, as well as also having specific habitat specialisations. Also, all but one of the collapsed fisheries are slow breeders. All collapsed fisheries apart from orange roughy were challenged by disease, and their high economic value was considered a negative impact on the stock (i.e. motivating IUU fishing). The depleted South African toothfish scored high for biology, environment and management but very low for socioeconomic and governance criteria (4f). The eel fishery was the epitome of the scores for the collapsed fisheries, scoring low for all the six variables (4d), while the cod fishery in Canada was distinctly different from the others - with medium, high or very high scores on all variables (4e).

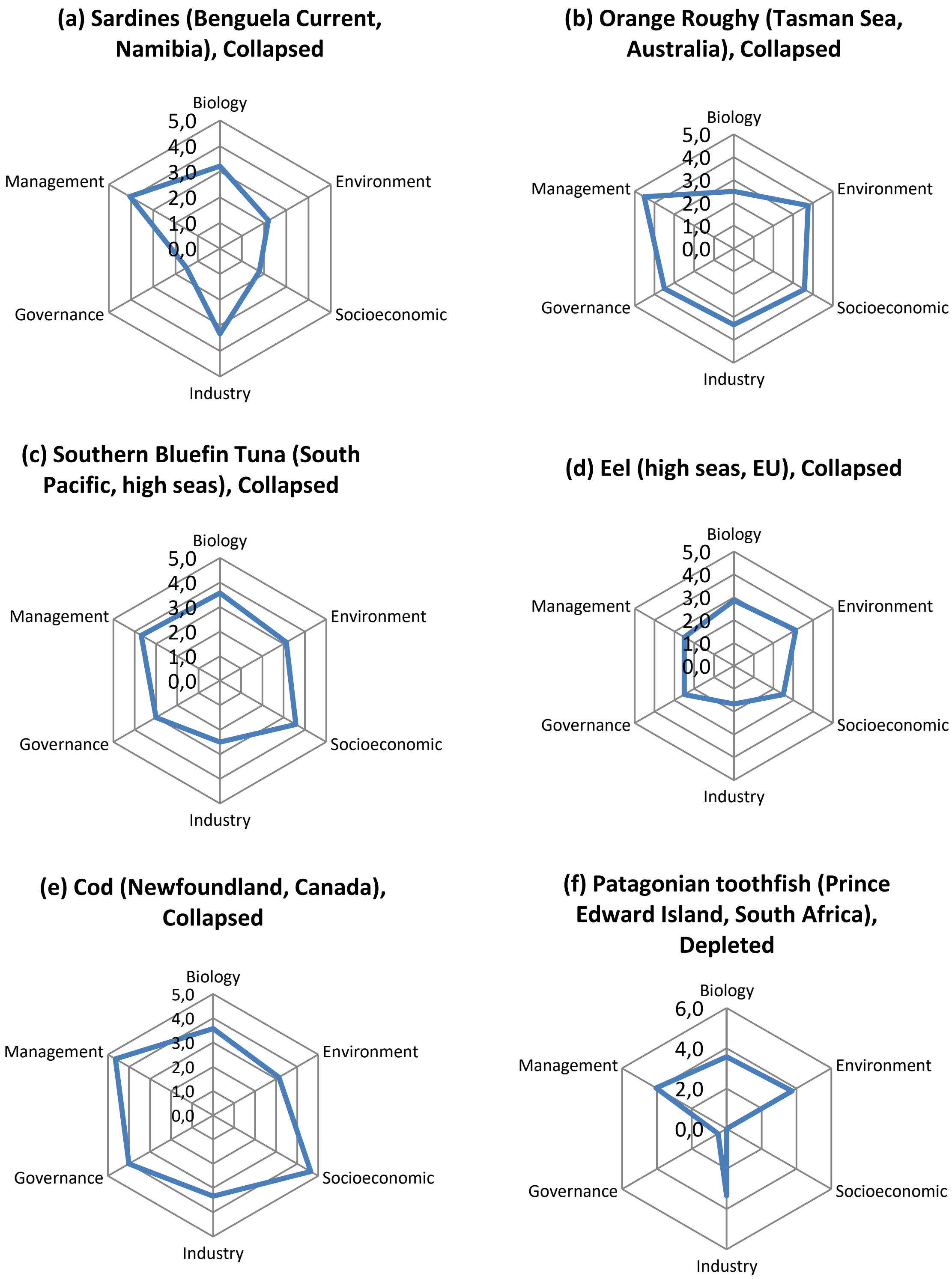


Figure 4a-f: The average scores for the six variables for the collapsed and depleted fisheries.

Almost all of the 15 sustainable fisheries got high scores for all the six variables, whilst the collapsed/depleted ones had a wider variability of scores among the variables (Fig. 5a).

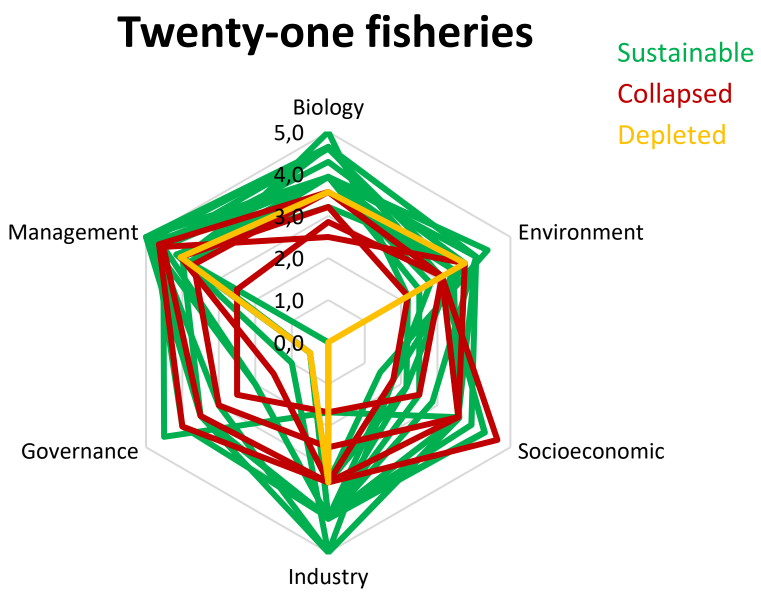


Figure 5a: The sustainable fisheries mostly ranked high on all the six variables.

Based on mean values, the major differences between sustainable versus collapsed/depleted fisheries for the six variables were biology, environment and industry (Fig. 5b).

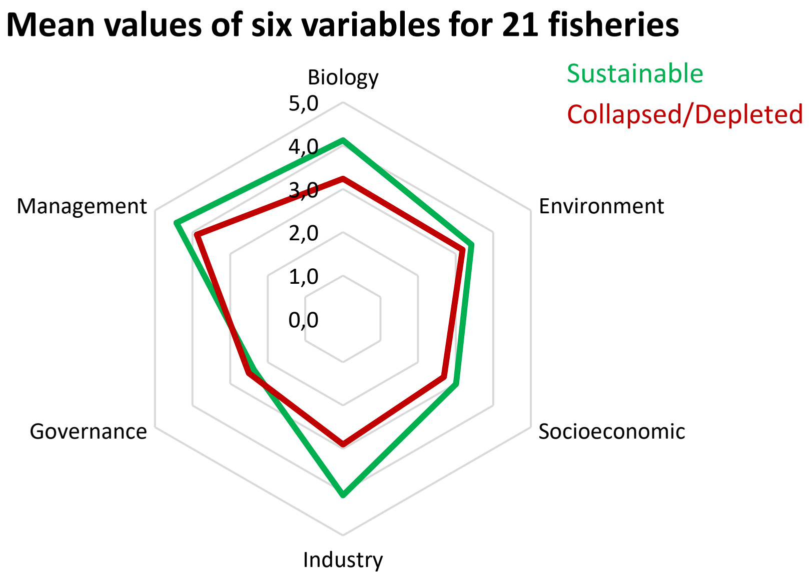


Figure 5b: Mean values of the six variables for the 15 sustainable and the 6 depleted/collapsed fisheries.

Discussion

The analysis showed a clear separation between collapsed/depleted and sustainable fisheries, although there were differences within a stock status category (Fig. 2). We also discovered that sustainable fisheries (Alaska Pollock, cod EU, cod Iceland, cod Norway/Russia, herring, Northern Prawn Fishery, Australian toothfish, South Georgia toothfish, rock lobster WA), and collapsed fisheries (cod in Canada, orange roughy) could score highly on management criteria, suggesting either that characteristics of management alone are insufficient to determine stock status, that management responses in the collapsed/depleted fisheries had been invoked too recently to have yet had much effect on the stock, or that management gets it wrong. Seven of the nine fisheries with high management scores had a paid quota system. The collapsed eel and southern bluefin tuna fisheries, both exposed to IUU fishing particularly in the high seas, had a low overall score, specifically for industry, governance and management. All but one of the depleted and collapsed fisheries scored very highly on management, confirming that sustaining and recovering fish stocks is a challenging task (Hilborn et al. 2013).

Of the 21 fisheries analysed almost all of the 15 sustainable ones got high scores for all the six variables, whilst the collapsed/depleted fisheries had a wider variability of scores among the variables. When faced with the challenges of marine resource management, both managers and other stakeholders need to identify the conditions that contribute to sustainable fisheries. Is the Australian Northern Prawn Fishery sustainable because biological traits are very well known? Is it sustainable because management works closely with researchers and industry? Is it sustainable because there is an effort control system in place, controlling over-capacity? Is it because the fishery has moved to an MEY target reference point, which is more conservative than an MSY target point (potentially making the fisheries more resilient)? In all likelihood it is a mix of all.

The analysis showed that within the three groups of fisheries (sustainable, depleted and collapsed) the overall scores had a wide range, revealing wide variability in the capacity and process of fisheries management, and emphasising that high performance over a range of highly diverse variables are necessary to guarantee that a fishery has a high likelihood of sustainability. Equally, no single variable or criterion marks a fishery as prone to collapse. Rather it is the combination of a set of factors involving biological and environmental knowledge, governance and management impacts, socioeconomic and industry parameters. Even when a wide selection of management tools, including effort and harvest controls are in place, together with social and economic considerations are in place, a stock may still collapse (due, for example, to a lack of stock data on growth and recruitment rates, or data on age at maturity), as has occurred spectacularly in both the cod fishery in eastern Canada and the orange roughy in Australia. At the other end of the spectrum, fisheries that might not have the same degree of management measures in place, such as the Peruvian anchoveta, may remain robust due to their biological responsiveness to relatively quickly recover from decreases in biomass if no other stressors are present.

I found that across the 21 fisheries considered there was typically good biological knowledge of the fished stocks, a wide range of management tools (legal framework, management agency, use of TACs, catch and gear restrictions, stock assessment and spatial management), and industry incentives (in particular a paid quota system) were present in some form. This does not mean all fisheries were similar and while all 21 fisheries have a legal framework and a marine management agency in place, it was not possible to investigate how effective compliance with the frameworks was. In addition, all but one of the collapsed/depleted fisheries have high scores for management criteria, which could be a direct result of initiating additional management actions in response to the collapse (or in an effort to avert it). It could also be that it takes time to fully implement management tools and for an increase in stock abundance to occur.

Not surprisingly, all but one of the sustainable fisheries investigated had a viable size/age distribution, while none of the collapsed ones and the depleted one had not. The single exception, was the WA rock lobster which was coming off an extended period of poor recruitment due to climate drivers (de Lestang et al. 2014).

Interestingly, the collapsed fisheries all had a medium-high risk of IUU fishing, while all the sustainable fisheries had a low-medium risk. This supports the idea that (i) high valued species are prone to IUU fishing, (ii) but with appropriate measures the risk of IUU may be reduced, and that (iii) high presence or risk of IUU and corruption is a clear marker of a fishery in trouble (as it does not have the will or capacity to enforce regulations) (Schmidt 2005, Le Gallic et al. 2006).

Biology and environment

Biology was one variable that showed high scores for all of the sustainable fisheries. This is not surprising, as fundamental knowledge about a species biology and the environment in which it lives is essential for identifying the appropriate management tools that are needed to obtain sustainable fish stocks in the long-term (King 2013). It is clearly important that a stock has a viable size and age distribution that can support exploitation and rapidly recover from overshoots or stochastic events that may exacerbate downturns (Enberg et al. 2009). Here the analysis showed that all but two of the collapsed and depleted fisheries are slow breeders, suggesting that it is harder to manage or recover species that mature late (Heppell et al. 2005). This research further supports the finding that maintaining a viable age/size distribution is essential for long-term sustainable fish stocks (Berkeley et al. 2004, Hilborn and Walters 2013).

Ongoing monitoring of environmental variables in the context of fisheries is clearly important in managing for sustainability. For example, the rock lobster in Western Australia has one of the world's longest time-series of abundance estimates, and it is generally considered that appropriate conservation measures were in place (Penn et al. 2015) including precautionary fishery adjustments based on responses to observed levels of recruitment (puerulus settlement) (de Lestang et al. 2014). Additional significant changes occurred in this fishery following a marine heat wave (Pearce et al. 2011) and this flags that even if a species has been sustainable in the past it might not be under environmentally altered conditions – or at least they may not be sustainably exploited to the same levels as in the past.

Social and economic conditions

The collapsed Canadian cod fishery had the highest socioeconomic rating of all the 21 fisheries investigated, suggesting that the considerable management resources available was due to the fact that the fishery was recognised as vital for sustaining fisheries-dependent communities in Newfoundland and Labrador (Bavington 2011). This could also have put pressure on politicians to permit ongoing fishing since fishing was the main industry sustaining these communities. While the rock lobster fishery in Tasmania also had a high socioeconomic score (4.3), its sustainability may reflect the smaller size of fishing-dependent communities and the close collaboration between the government, industry and independent researchers (Johnson et al. 2013, Marzloff et al. 2016). However, it is worth noting that since the time of our analysis, an increase in the frequency of extreme climate events around Tasmania has put into question the status of this stock (Marzloff et al. 2016).

Management and governance

Governance in this analysis showed both high and low scores within all three categories of fisheries. The seabob fishery in Suriname is MSC certified, showing that an external validation system can help overcome issues associated with corruption and management to achieve a sustainable fishery. However, there is no guarantee that MSC certified fisheries in developed nations with low corruption will remain sustainable, as exemplified by the Eastern Baltic cod managed by the EU, which lost its MSC certification in 2015 (MSC 2015) after the analysis we present here was completed. Given the variability in environmental factors, such as oxygen and salinity, in this area that affect cod survival rates (Köster et al. 2005), and the challenge with overfishing and potential collapse that already existed prior to the MSC certification (Lindegren et al. 2009), it is not surprising that this fishery is no longer classified as sustainable.

The fisheries studied here are long-term commercial fisheries with a large range of management tools in place. The fact that all fisheries considered in this analysis scored high for most of the management criteria may simply reflect that only commercially highly valuable stocks (which tend to attract management efforts) had sufficient data available to be included in the analysis. That more than 80% of the world's catch lacks adequate stock assessment should clearly be cause for significant concern (Costello et al. 2012, Costello et al. 2016). The main reason for this may be that both data availability and assessments are limited in some parts of the world, but despite these data poor fisheries, about 33% of the world's fisheries were classified as overfished in 2015 (FAO 2016).

Differential success in the implementation of management of the surveyed fisheries, including monitoring and adaption, is reflected in that some stocks are depleted or collapsed despite application of many of the recommended 'best practice' management tools. In addition, current management methods may be in place in an effort to avert collapse or recover from it. The Atlantic cod fishery of Newfoundland and Labrador is often used as an example for mismanagement leading to collapse (Milich 1999). Our analysis showed that although the fishery scored highly on management, governance, and socioeconomic criteria, the stock did not have a viable age/size distribution. This was possibly due to the fact that the annual survival probabilities had a twofold decline in the 1980s, which occurred at the same time as declining catch rates, and increased effort in both in- and offshore fishing (Hutchings et al. 1994). Even though large resources in terms of governance and management were not able to set a TAC to sustain the fishery and prevent a collapse in the 1990s, the management efforts since are most likely to have contributed to an increase in abundance and size composition some 25 years after the moratorium in 1992 (Rose and Rowe 2015).

Industry

A majority of the sustainable fisheries (the exceptions being the Northern Prawn Fishery and Antarctic toothfish within the CCAMLR convention area) were based on individual property rights. All the fisheries - except for the collapsed eel fishery and the Baltic cod fishery - had a system where fishers have to pay a fee to fish (including a membership fee paid to a management organisation such as CCAMLR). These two findings support other studies of how Individual transferable quotas (ITQs) and license fees can be an effective management tool, providing the TAC is sensible, together with other conservation measures, to combat overcapitalization and overfishing (Branch 2009, Färe et al. 2015).

While there is always a risk of IUU fishing, particularly for high-valued species, an ITQ system might be one tool to also sustain the social and economic goals of fisheries, provided that the available biological information allows for the setting of a sensible TAC (Schaltegger and Wagner 2017). One example of this is the South African Patagonian toothfish. IUU fishing was first detected in this fishery in 1995, but is believed to have started in 1994, with IUU catches estimated to be higher than the legal catches (Brandão et al. 2009). Measures implemented to combat the IUU fishing included a paid quota scheme as well as participation in CCAMLR's catch documentation scheme. Despite these measures, retrieved illegal fishing gear and observed IUU vessels confirms that IUU fishing persists in the area (CCAMLR 2015). Stock abundance and potential recovery is uncertain, not only because of IUU fishing activities but also because different types of stock abundance measuring methods have been used (CCAMLR 2015).

The toothfish fisheries

The four toothfish fisheries studied here are underpinned by different management organisations. Three of the fisheries are managed by individual nations (Australia, South Africa, the United Kingdom). In contrast, the Ross Sea toothfish fishery is more at risk because it is a straddling stock, and CCAMLR's member states have mixed anti-corruption weightings (3 members are rated as 'highly corrupt' and 11 as 'moderately corrupt') (Nilsson et al. 2016), which suggests that the behaviours of members and fishers and their willingness to comply with measures and regulations may be variable.

The mostly deep-water Antarctic and Patagonian toothfish have complex life histories including late maturity, high interannual variability in reproductive traits, specific habitat use and movement over its more than 50 year life span, making them particularly vulnerable to overfishing as any recovery process would be long (Péron et al. 2016). Toothfish, or 'white gold', is also a highly valued species making it particularly sensitive to IUU fishing, both by licensed and non-licensed operators. Although a large range of management measures are in place – including Total Allowable Catch (TAC) and Vessel Monitoring Systems, together with a scientific observer program and a catch documentation scheme (CDS) – IUU fishing in the Southern Ocean remains a problem (Miller et al. 2016). Further support for this is a study showing that 76% of fish on a Chinese market was mislabeled to overcome the CDS in place by CCAMLR for Patagonian toothfish (Xiong et al. 2016). Despite Australia and France using armed patrol vessels (in French and Australian territorial waters of the Southern Ocean) IUU fishing of toothfish may be far from being eradicated (Clare 2010).

The three sustainable toothfish fisheries we analysed showed that the Ross Sea fishery has a low anti-corruption index. This may imply that the fishery in the Ross Sea is at risk as there is a high risk for corruption (i.e. IUU fishing). The overall decrease of Patagonian toothfish in the Southern Ocean has occurred because this high-valued species is profitable even when illegally caught (although few sightings have been reported in the last few years), and there is a low risk of being caught (Agnew et al. 2009, Brooks et al. 2017). The Ross Sea toothfish was defined as sustainable, mainly because of the conservation measures in place by CCAMLR, but had a low overall score. Even though the value is high (even on the illegal market), this fishery may remain sustainable due to the 1.55 million km^2 MPA that was implemented in the Ross Sea on 1 December 2017, with a 1.2 million km^2 no-take zone (CCAMLR 2015).

The toothfish fisheries managed by CCAMLR may be at risk as toothfish matures late, has low fecundity rate, and is slow-growing (Collins et al. 2010); CCAMLR has no ITQ system in place; there also is no, or little, control of actual catches (the observers record some scientific data, not actual catches); there is low reporting of by-catch; and there is evidence of IUU (Ainley et al. 2012, Ainley et al. 2014, Xiong et al. 2016).

The cod fisheries

The four cod fisheries we examined are all managed by developed countries. The two sustainable cod fisheries in Iceland and Norway/Russia scored highly on the industry, management and biology criteria. In addition to the management tools in place for these fisheries, the warming water allowing changes in distribution and higher survival and recruitment levels might also be factors influencing the observed increase in abundance of the two stocks (Budreau et al. 2007).

The other two cod fisheries (Canada and Baltic Sea) are collapsed or depleted. Both of these classes of fisheries score high on the governance, management and biology criteria but they score low on industry, suggesting that economic measures and incentives may be useful in managing effort, as was seen for the sustainable Northern Prawn Fishery.

The Australian fisheries

For the five Australian fisheries analysed here four are sustainable and one is collapsed. The sustainable MSC certified Patagonian toothfish in Australia's sub-Antarctic territory scored very high for management, biology and industry, and the sustainable Northern Prawn Fishery was a standout, scoring very highly for biology, environment, management, industry and socioeconomic variables.

The collapsed deep-sea orange roughy was closed in 2006 (apart from on the Cascade Plateau) (AFMA 2014), and this late maturing species (27-32 years of age) has yet to fully recover (AFMA 2015), although a controlled fishery reopened in Tasmania's east coast in 2015. This emphasises that even when management is adaptive and enforces a moratorium, recovery and rapid turnaround is not guaranteed - biology will play its part.

The rock lobster fisheries are both sustainable at present, but we note that both are now struggling with direct or indirect impacts related to climate change (Caputi et al. 2009, Johnson et al. 2011, Pecl et al. 2017), highlighting the new suite of challenges facing resource managers even though they are well armed with long-term data sets and relevant management tools.

Developed vs developing economies

There was no material difference in the performance of fisheries across developed and developing economies for the fisheries considered in this study, suggesting that management and compliance is more important than governance. For example, sustainable fisheries with high or very high scores for management but with very low governance scores were found in USA, Peru, South Africa, Russia, Suriname, and the high seas. Clearly, it takes more than a high anti-corruption index and a transparent governance structure to sustain fish stocks long-term.

Conclusions

Sustainable, depleted and collapsed fisheries are all present in both developed and developing parts of the world. As depleted and collapsed fisheries may not easily recover - causing high biological, economic and social costs – it is imperative to understand the risk factors so that they can be addressed. The fisheries analysed in this paper have all faced changes driven by ecological, economic and social factors. The analysis of these fisheries shows that priorities for sustaining fisheries include: i) identifying whether the stock has a viable size / age distribution, as without it stocks risk being depleted no matter what management tools are in place; ii) the sustainable fisheries showed that ITQs played an important part (given the TAC is estimated appropriately); iii) developed and developing nations both had sustainable and collapsed fisheries; and iv) even when a moratorium is in place a stock may recover very slowly as seen with the Canadian cod fishery and the Australian orange roughy fishery.

The analysis showed that all but one of the sustainable, depleted, and collapsed fisheries had very high scores for the 21 management criteria. However, this analysis also showed that although a fishery might have a high score for management, without a medium or high score for biological knowledge, including age / size distribution, sustainability is difficult to achieve. In developing nations with a higher risk of corruption, achieving sustainable fisheries is still possible with sound scientific and management processes and commitments in place, as there is no guarantee that overexploitation will not occur in developed nations with plenty of scientific and management resources deployed. The criteria that overall defined differences between sustainable and collapsed fisheries are, in particular, 'age-size', but also commercial value, closures, certification and, to some extent, a lack of disease. The sustainable fisheries all had high scores on biology, management, and industry criteria. None of the collapsed fisheries had a similar pattern of scoring across the six variables, supporting the notion that different fisheries can collapse for different reasons, that managing marine resources is complex, and that an adaptive approach with explicit attention to all of the variables we identified here is essential to maximise the likelihood of achieving sustainable practice in commercial fisheries.

Supplementary material

The following supplementary material is available as appendices:

- *Appendix 1: Supplementary material 1 - Criteria scoring.* In this document the variables and associated criteria are defined, with a scoring system (0, 1 or 2);
- *Appendix 2: Supplementary material 2 - Raw data, Meta-analysis 21 fisheries. This document shows the scores for each of the 51 criteria per fishery;*
- *Appendix 3: Supplementary material 3 - References to scores (0-2). This is a reference list to each of the 51 scores per fishery.*

Chapter 3: How to sustain fisheries: Expert knowledge from 34 nations

Abstract

Ensuring productive and sustainable fisheries involves understanding the complex interactions between biology, environment, politics, management and governance. Fisheries are faced with a range of challenges, and without robust and careful management in place, levels of anthropogenic disturbance on ecosystems and fisheries are likely to have a continuous negative impact on biodiversity and fish stocks worldwide. Fisheries management agencies, therefore, need to be both efficient and effective in working towards long-term sustainable ecosystems and fisheries, while also being resilient to political and socioeconomic pressures. Marine governance, i.e., the processes of developing and implementing decisions over fisheries, often has to account for socioeconomic issues (such as unemployment and business developments) when they attract political attention and resources. This paper addresses the challenges of (Jackson et al. 2001) identifying the main issues in attempting to ensure the sustainability of fisheries, and (Halpern 2008) how to bridge the gap between scientific knowledge and governance of marine systems. Utilising data gained from a survey of marine experts from 34 nations, we found that the main challenges perceived by fisheries experts were overfishing, habitat destruction, climate change and a lack of political will. Measures suggested to address these challenges did not demand any radical change, but included extant approaches, including ecosystem-based fisheries management with particular attention to closures, gear restrictions, use of individual transferable quotas (ITQs) and improved compliance, monitoring and control.

Introduction

For the second half of the twentieth century, scientific and technological endeavours focused on finding new fisheries to exploit and more efficient and effective ways of harvesting. This was possible as developments in vessel and gear design, navigation and positioning systems and means to detect fish (e.g., depth-sounders) became more accessible to the common fisher (Jackson et al. 2001). These scientific and technological advances led to a dramatic increase in global fishing effort. Such developments also allowed fleets to exploit more distant resources to the point where the only unexploited fishery resources were those that remained physically inaccessible, for example under sea-ice (Halpern 2008). For much of this period, much of the sea was treated as a common resource with many fish stocks exploited with little restriction and only a few with strict governance, setting conditions for a “tragedy of the commons” (Hardin 1968). In recent decades, there has been increasing awareness of the need for global political action on natural resource management, as evidenced by the Rio Declaration on Environment and Development in 1992 (UNESCO 1992) and by such initiatives as the Oxford Martin Commission for Future Generations, launched in 2012 by an interdisciplinary group of organisations (Moss et al. 2010).

By the latter decades of the twentieth century, it became apparent that the substantial increase in fishing capacity was leading to overexploitation and, in some cases, collapse of fisheries (Pauly et al. 2002, Mullon et al. 2005). Overfishing, with associated ecosystem shifts, is a major threat to the marine environment. More than half of the world’s marine fish stocks are considered to be either overexploited or fully exploited with no room for further expansion [8]. Although stocks have been fished for a number of centuries, the sheer number of global stocks that are currently below sustainable exploitation levels is unprecedented (FAO 2013, FAO 2016). Failure to understand and sustain ecosystem processes, including human impacts upon them, continues to cause major biodiversity loss in many places around the globe (Worm et al. 2006, Fulton et al. 2011, Jones et al. 2014, Tittensor et al. 2014, McCauley et al. 2015). As a result, a number of scientific initiatives are directed towards developing and applying methods to better measure, predict and monitor sustainable yields of key fish stocks, in both national and international waters (Pauly et al. 1998, Pauly et al. 2002, Johnson et al. 2015).

Public demand for marine management

Over at least two decades, there have been increasing calls from scientists, nongovernmental organisations (NGOs) and the public at large for better management of marine ecosystems. These calls have partly been based on scientific research that has revealed the myriad ways that fishing activities (along with climate change, terrestrial runoff and other anthropogenic processes) impact the overall health of marine ecosystems (IPCC 1998, Pikitch et al. 2004, FAO 2013). Increased environmental awareness has led to calls for attention to ecosystem-focused approaches to management, variously termed the Ecosystem Approach to Fisheries (EAF) (FAO 2016), Ecosystem-Based Fisheries Management (EBFM) (Slocombe 1993, Polasky et al. 2011), or cross-sectoral Ecosystem-Based Management (EBM) (i.e., spanning all marine sectors, not just fisheries) (Polasky et al. 2011).

Despite an increase in scientific knowledge and management efforts on overexploited fisheries and marine systems, there are still ecosystems and fish stocks showing no or little sign of recovery. It is recognized that impacts on the marine environment from fishing pressure might, in some cases, be more severe than first thought (Bradshaw and Borchers 2000). This calls for fisheries to be governed and managed holistically, needing a combination of environmental, biological and socioeconomic research to provide robust marine governance and management strategies to ensure a sustainable marine environment. The gap, however, between science and policy has been acknowledged (Haward 2011, Bertuol-Garcia et al. 2018), as has the fact that governance and management decisions are not always based on the best science available (Hoegh-Guldberg and Bruno 2010).

The challenge of ecosystem-based management: Predicting uncertainties

Apart from fishing pressure, marine ecosystems and fisheries are also subject to other effects of human activity, such as climate change, ocean acidification and related biophysical impacts, habitat loss and impacts from terrestrial land use, such as land-based sources of pollution and litter (Jones and Cheung 2014, Cloern et al. 2016). A key challenge is to predict the long-term effects of these cumulative anthropogenic impacts and to form appropriate management strategies (Melville-Smith 2011). Without appropriate knowledge and understanding of the ecosystem supporting fisheries, and the communities in which fisheries are embedded, it is likely that management will fail (Fulton et al. 2011).

The complexity of governing and managing fisheries in a socioeconomic context was illustrated by the 2009 Nobel Prize in Economics. The Nobel Prize was shared between Dr Ostrom, whose research was based on the assumption that people in a community can create successful agreements (and compliance) for managing common use of natural resources, such as fisheries (Ostrom et al. 1999), and by Dr Williamson, who presumed that natural resource management needs a top-down management approach because individuals ultimately cannot trust one another (Earl et al. 2011).

Another challenge (at times the largest challenge) for fisheries and environmental managers is a lack of political will to use and implement recommendations based on scientific findings. This challenge can reflect and reinforce the 'science–policy gap' (Bertuol-Garcia et al. 2018). Although scientists may make management recommendations based on their findings, ultimately management decisions are made by government officials and politicians. Importantly, these decisions are not driven only by scientific knowledge of the stock and dynamics of the ecosystem in which a fishery is embedded, but also by a range of political agendas and economic, social and cultural considerations. While scientists may be frustrated with this reality, it is important for them both to accept that they are only one voice at the decision-maker's table, but also not to shy away from objectively presenting the scientific evidence.

Given that there are many environmental, biological and socioeconomic factors that ultimately affect the state and health of the oceans, and that these drivers vary in time and space, decision-makers increasingly ask whether there is sufficient scientific information and knowledge of ecological functions and processes to implement an ecosystem approach to marine and fisheries management (Lester et al. 2010, Tallis et al. 2010, McLeod et al. 2011). Successful marine management needs careful integration across sound scientific knowledge, development and implementation of management instruments and compliance tools. Even though there are many ecological processes to understand further, it is widely recognised that we do have sufficient scientific information to start implementing EBFM in many places around the world (Mardle et al. 2004, Pascoe et al. 2009, PAME 2017).

One challenge to implementing EBFM is that ocean resources are often managed sector-by-sector, i.e., coastal and terrestrial development, water management, environment conservation and primary industries (including fisheries) are each managed by separate jurisdictions (Tallis et al. 2010). The different set of goals and objectives within each sector may have implicit trade-offs so that fisheries managers often need to navigate and respond to conflicting objectives and incentives involving two or more government agencies (Halpern et al. 2008, Nilsson et al. 2016) or interest groups. Clearly, if there is a negative impact on marine habitat due to fishing gear as well as from toxic terrestrial run-off, then both the fishing sector and the land-use sector need to take appropriate actions to prevent further habitat degradation (Marshall et al. 2018). Implementing EBFM, or EBM, requires a governmental organisational structure that matches this holistic view of ecosystem-based management. This does not immediately dictate an overarching, all-encompassing regulatory body, but it does necessitate communication (and where possible harmonisation of requirements) between agencies.

While defining the final scope of an ecosystem-based management governance system is beyond the scope of this paper, providing information on the current state of play is important to understanding what steps are still required to achieve solid advances. This research explores the main issues influencing the sustainability of fisheries. It draws on data derived from an international survey of fisheries experts, using the elicited responses to (1) identify the main issues in attempting to ensure the sustainability of fisheries, and (2) address how to begin to bridge the gap between scientific knowledge and the governance of marine systems, from the point of view of fishery management experts. The survey data were analysed to explore expert insights, opinion and understanding on the challenges to sustainable fisheries, the efficacy of tools used to manage fisheries and the complexity of interactions in fishery socioecological systems.

Methods

Data collection

I targeted marine experts from around the world, primarily scientists and natural resource managers. Our survey was designed to elicit knowledge from marine scientists, managers, fishers and policy-makers. The intention was to gather specialist knowledge and experience in relation to sustaining fisheries. The survey was implemented by inviting experts to share their knowledge and experiences at the 6th World Fisheries Congress in Edinburgh, 8–11 May 2012. Attendees were invited to sit down at a booth and take part in the web-based survey. If an individual did not have time to conduct the survey when approached, they were given the opportunity to complete the survey in their own time either online or via a hard-copy of the survey. In total, 549 persons were invited to participate in the survey, resulting in 168 fully completed surveys (20 more provided partial completions that were still sufficient for inclusion in the analysis), giving a 34% response rate.

Analysis

The questions and a summary of the answers are presented in Appendix 4. Given small sample sizes when respondents were broken down by category, for some questions, the responses from fisheries/natural resource managers and policy-makers were aggregated into a 'managers/policy makers' group. For the same reason, variables measured on five-point response scales were, in some cases, converted into a three-point scale. For example, the five-point 'satisfied-dissatisfied' scale was in some cases collapsed into the categories 'satisfied', 'neutral' and 'dissatisfied', by combining 'satisfied' with 'very satisfied', and 'dissatisfied' with 'very dissatisfied'.

Statistical analyses, including crosstabulations, were conducted using SPSS (Version 25.0., IBM Corp, Armonk, NY, USA). No corrections were made. The statistical independence of pairs of variables was analysed using the 2-factor G-test for independence at a 95% significance level.

Results

Demographics

The respondents were from 34 nations, representing scientists, fisheries managers, fishers, policy-makers, NGOs and others. Forty (40) respondents were from Australia, as the survey was trialled there before presenting it at the World Fisheries Congress.

Seventy-one percent of the respondents were male, and 60% of the respondents were 35–64 years old (Appendix 4). Forty-two percent of the respondents had a Doctoral degree, 28% a Master's degree, 14% a 3–4 year university degree, and the remainder did not hold a degree, but all had completed high school (Appendix 4). The majority of the respondents were scientists (Fig. 1), with fifty-nine percent of the respondents holding a degree in marine science and 20% in environmental science. Other respondents had degrees in business, law, economics and social sciences (Appendix 4).

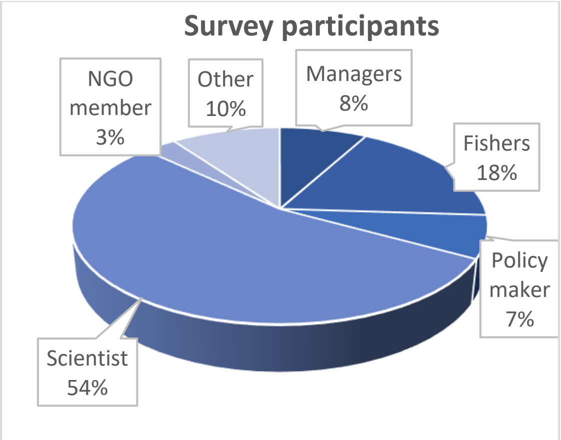


Figure 1: The breakdown of respondents by profession (n = 177). 'Other' includes consultants, economists, social scientists, lawyers and students. NGO, nongovernmental organization.

The majority of the respondents spanned middle-executive management positions, and represented pelagic, demersal, coastal and crustacean fisheries (Fig. 2 and Fig. 3). The respondents represent experience and knowledge from fisheries deemed to be sustainable as well as from overfished, collapsed, recovering and exploratory fisheries (Fig. 4). Of the respondents, 47% worked with national management agencies, 24% with international management and 15% at universities (Appendix 4).

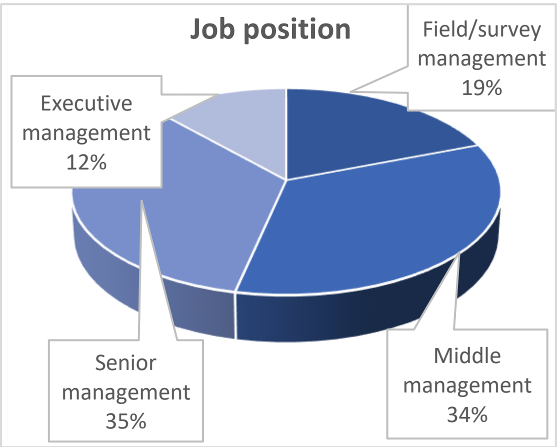


Figure 2: The job position held by respondents (n = 146).

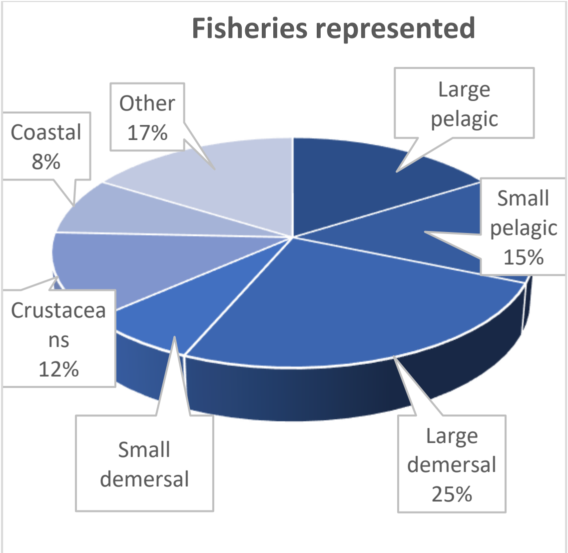


Figure 3: The fishery types covered by survey respondents. 'Other' includes shark, inland, aquaculture and shellfish (n = 143).

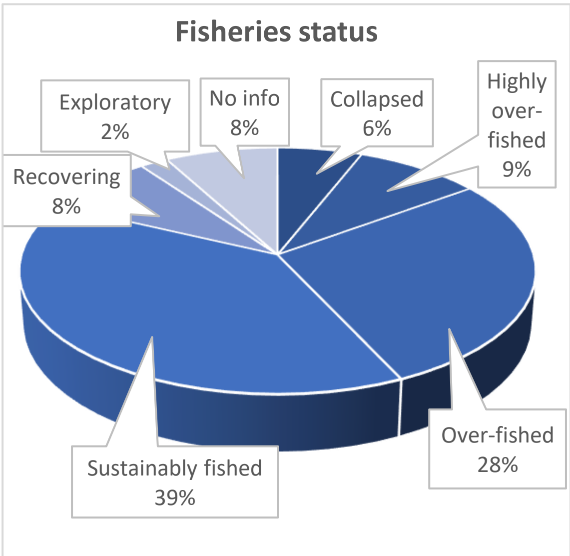


Figure 4: The status of the fisheries the respondents are working with (n = 172).

Anthropogenic effects on fisheries and marine Systems

Overfishing, climate change and habitat destruction were believed to be the three threats most affecting fisheries, both at national and global scales (Fig. 5). There was no significant difference among the responding groups as to whether or not they perceived the same 10 threats as major threats to national and world fisheries ($G = 10.191$, $df = 9$, $p = 0.335$), where G is the likelihood-ratio, df the degree of freedom and p the probability value.

Overfishing was believed to be a major threat to world fisheries by 79% of the managers, 92% of the policy-makers, 79% of the scientists and 84% of the fishers (Fig. 5). Notably, 69% of the policy-makers and scientists said they believe that illegal, unreported and unregulated (IUU) fishing is not a major threat to national fisheries, while 78% of the fishers said they think it is.

Fifty-eight percent of all respondents believed climate change to be a major threat to national fisheries, while 59% believed that ocean acidification is a major threat to world fisheries and 40% to national fisheries. Seventy-two percent of the fishers said they think habitat destruction is a major threat to the marine environment for world fisheries, while only 13% said it is a threat to national fisheries. Forty-one percent of the scientists believed land-based pollution is a major threat to fisheries, compared to 84% of the fishers, 85% of the policy-makers and 79% of the managers. Of all the respondents, 46% said plastic is a major threat to world fisheries (57% of managers and 62% of the scientists) and 30% said it is a major threat to national fisheries.

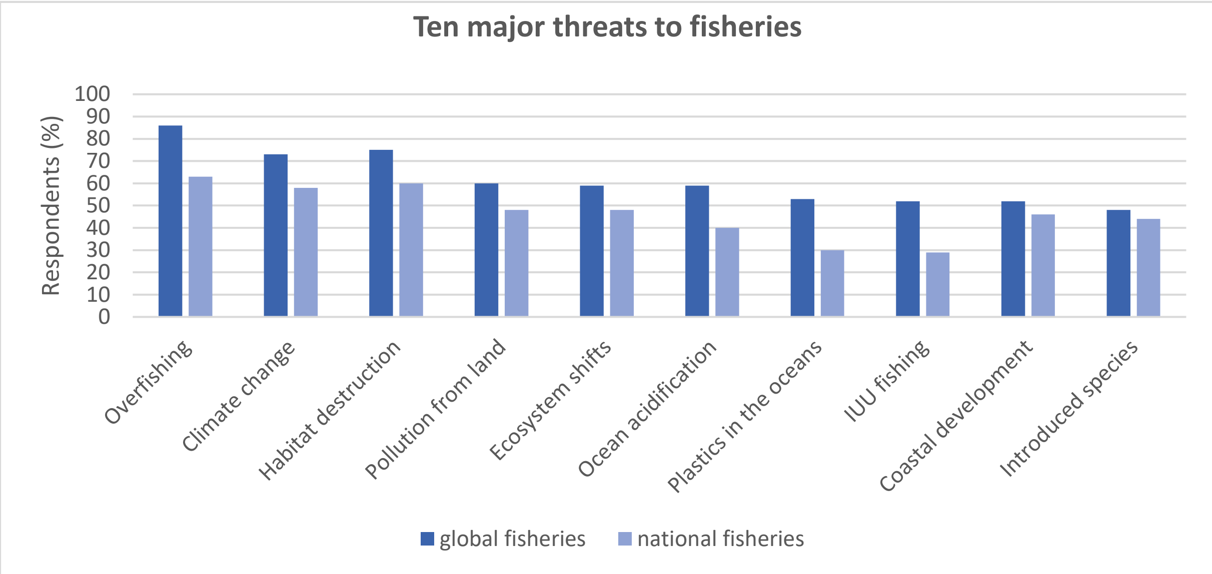


Figure 5: The 10 major threats to national and global fisheries (n = 164).

Despite the divergence in views in the earlier question pertaining to whether IUU is a threat to international or national fisheries, there was no significant difference among the responding groups on how they viewed the specific aspects of IUU fishing ($G = 61.275$, $df = 45$, $p = 0.054$). Corruption was seen as the main aspect of IUU fishing (66%), with 55% of respondents believing that there is insufficient compliance in place to combat IUU fishing (Fig. 6). Sixty-four percent said they believe IUU fishing is a problem within their fishery, and of those 43% said they think IUU fishing amounts to 6–30% of the total catch (Appendix 4). When specifically asked about IUU (rather than ranking it against other threats), on a global scale, 99% of the respondents believed that IUU fishing is a problem and 65% estimated the global level of IUU fishing to be between 31–60% of the total catch worldwide (Appendix 4).

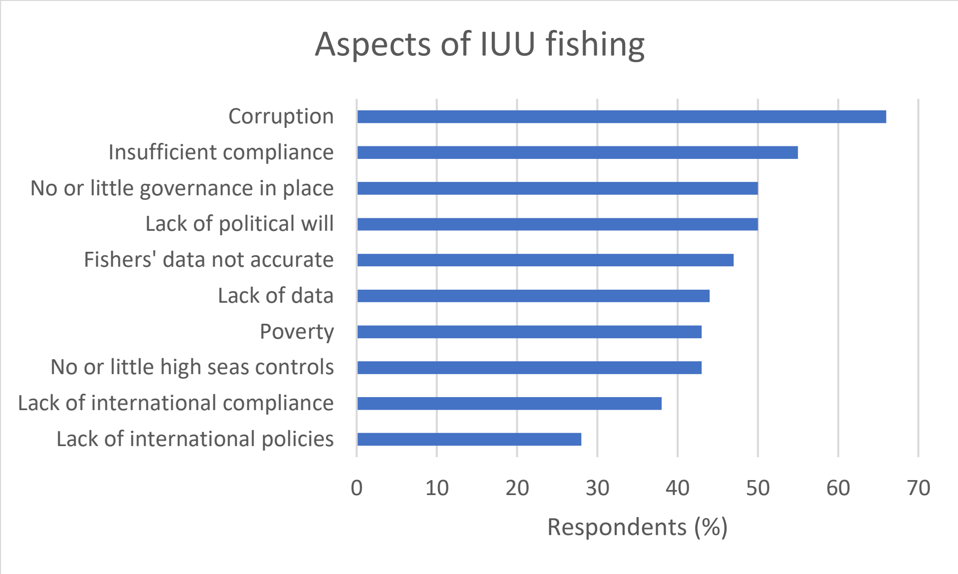


Figure 6: Key aspects of illegal, unreported and unregulated (IUU) problems identified by the respondents.

Fisheries governance and management affecting fisheries and marine systems

On the question of what the three main challenges to fisheries are, the following four factors ranked the highest: a lack of political will (56%); not enough compliance with regulations (33%); overfishing (29%); and stock assessment and monitoring (28%) (Fig. 7). There was no significant difference among the responding groups regarding which of the four factors were seen as the main challenges to managing fisheries ($G = 23.409$, $df = 15$, $p = 0.076$). Despite compliance being listed as a major challenge to sustainability, 90% of the fishers and 66% of the scientists said there is already enough compliance.

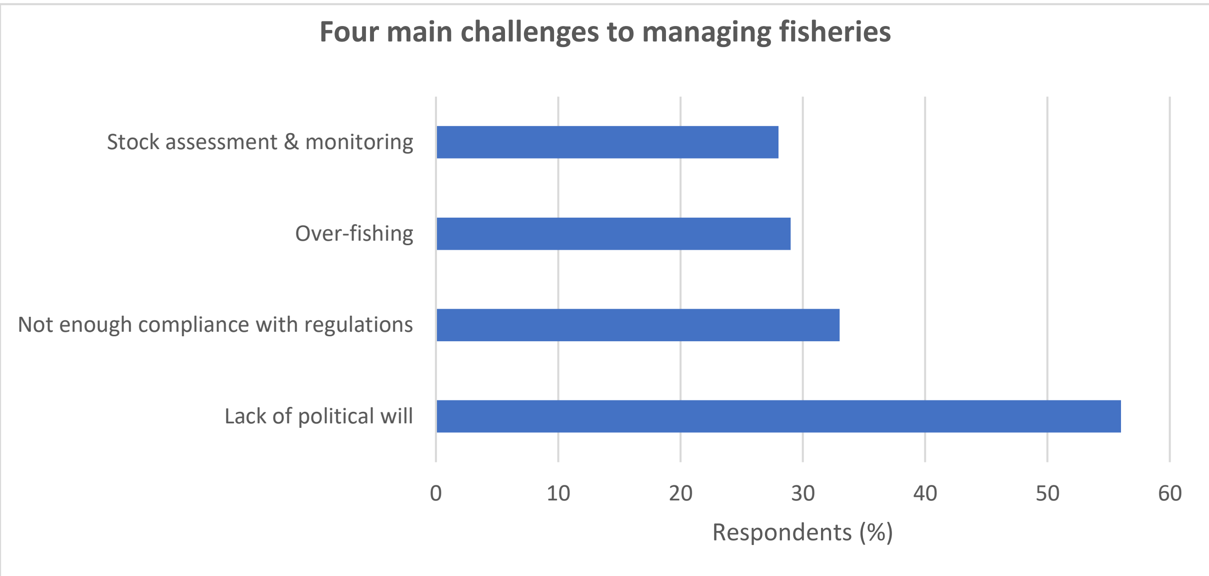


Figure 7: Expert opinions on four main challenges to managing fisheries (n = 174).

Fifty-five percent of the respondents believed that, during the course of their careers, they have seen major changes in fisheries management, such as increased input from scientists and industry, and stakeholder collaboration (Fig. 8).

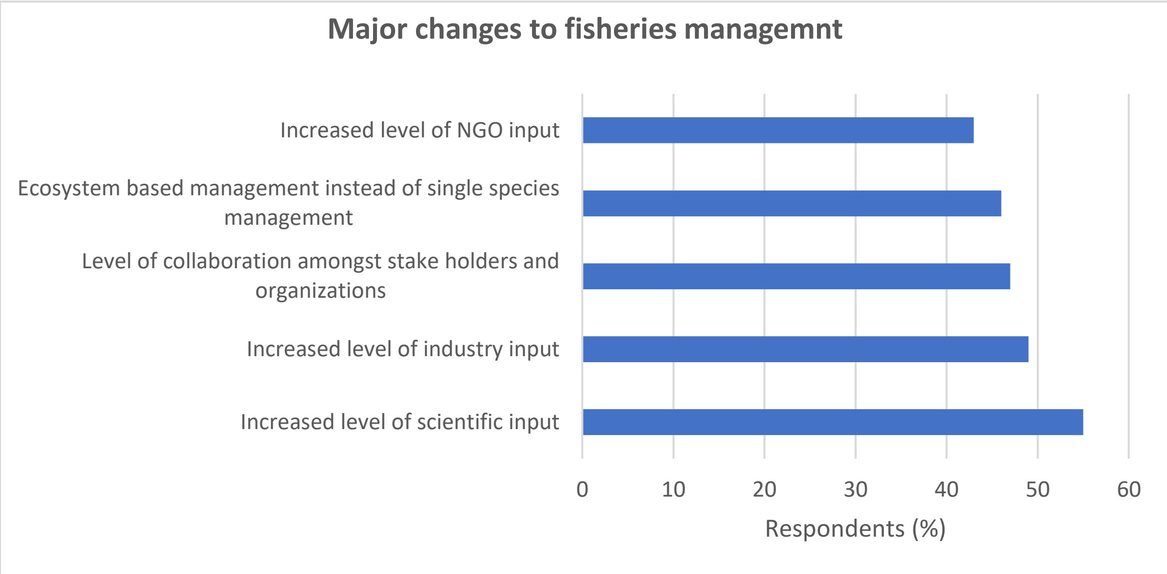


Figure 8: Major changes that have occurred in fisheries management during the respondents' careers in fisheries (n = 109).

More of the respondents were satisfied than dissatisfied with the planning and implementation of the EBFM processes. However, when considering the results of EBFM, a greater number of respondents were neutral, out numbering those who were satisfied or dissatisfied (Fig. 9). When looking to the fisheries they knew best, 60% of the respondents said that the fishery they worked with has implemented (EBFM) (Appendix 4), or a similar holistic approach to governing fisheries, though 50% said they were unsure as to whether the implementation of EBFM has been successful (Fig. 10).

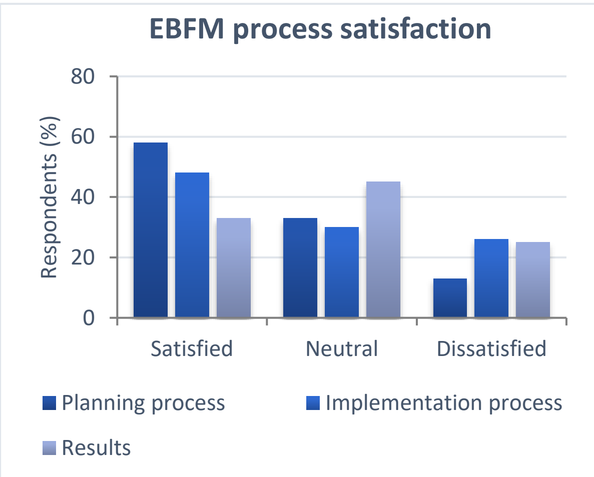


Figure 9: Measuring how satisfied the respondents were with the whole Ecosystem-Based Fisheries Management (EBFM) process (n = 104).

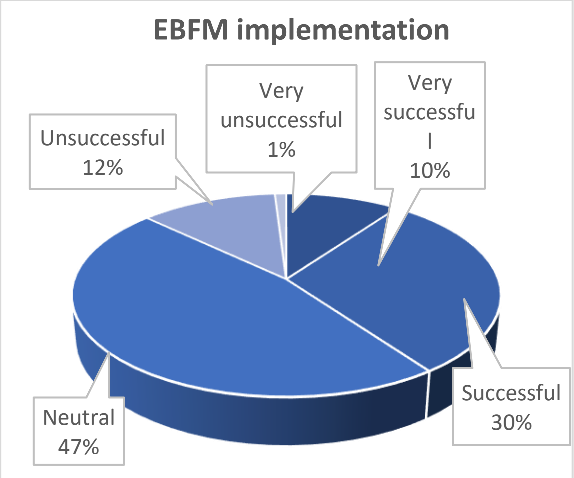


Figure 10: The perception of those respondents who said the EBFM process has been implemented regarding how successful the process had been (n = 107).

There was no significant difference among the responding groups in terms of their satisfaction with the planning processes associated with implementing EBFM (G = 11.358, df = 10, p = 0.33), with 73% of the managers, 67% of the policy-makers, 47% of the scientists and 50% of the fishers being satisfied. Thirty-eight percent of the scientists and 50% of the fishers were neutral. When it came to taking the step of implementing EBFM, there was also no significant differences among the responding groups on how they felt regarding this implementation process (G = 21.174, df = 15, p = 0.131), with approximately 50% of both the scientists and fishers being neutral.

Sixty-four percent of the managers and 58% of the policy-makers were satisfied with the results of implementing EBFM, compared with 31% of the scientists, 46% of the fishers and 0% of the NGOs (Table 1). About as many scientists as managers thought the implementation process of EBFM had been unsuccessful (Table 1) and about as many fishers as scientists remained neutral as to whether the EBFM implementation process had been successful (Table 1).

Table 1: The level of success for the implementation process of EBFM per responding group (% within each responding group. n = 108).

	Managers	**Policy-Makers**	**Scientists**	**Fishers**	**NGOs**
Very successful	0%	15%	11%	11%	0%
Successful	64%	31%	20%	35%	0%
Neutral	18%	39%	50%	54%	67%
Unsuccessful	9%	15%	19%	0%	33%
Very unsuccessful	9%	0%	0%	0%	0%

Once EBFM is in place (often in an adaptive management context), it is important to know if it is proving successful. When asked about this, there was no significant difference among the responding groups regarding how satisfied they were with the results of EBFM ($G = 16.571$, $df = 10$, $p = 0.084$): 55% of the managers were satisfied, compared with 23% of the scientists (Table 2). Of the fishers, 65% were neutral and 67% of the NGOs were dissatisfied (Table 2). Figure 11 shows that EBFM is challenging to implement, mainly because the process is highly complex.

Table 2: Satisfaction among the responding groups regarding results of the implementation of EBFM (% within each responding group. n = 104).

	Managers	Policy-Makers	Scientists	Fishers	NGOs
Very satisfied	0%	25%	2%	8%	0%
Satisfied	55%	17%	21%	23%	33%
Neutral	27%	33%	41%	65%	0%
Dissatisfied	9%	25%	29%	4%	67%
Very dissatisfied	9%	0%	7%	0%	0%

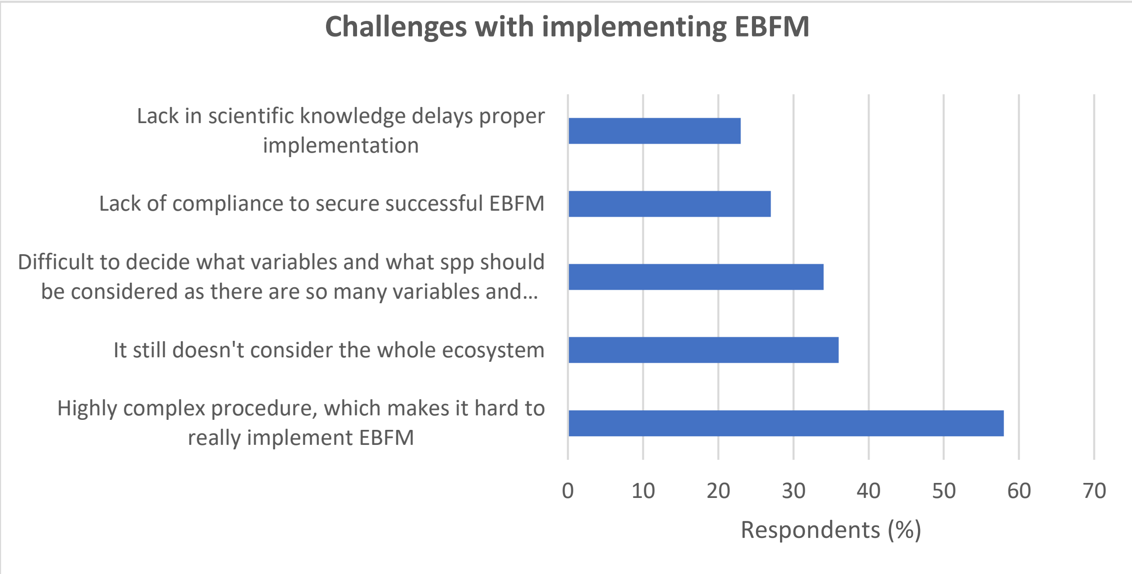


Figure 11: Implementing EBFM is a complex task (n = 83).

There was a significant difference among the responding groups regarding which tools are most efficient for implementing EBFM ($G = 44.226$, $df = 20$, $p = 0.001$). Respondents viewed good science, Marine Protected Areas (MPAs), individual transferable quotas (ITQs), gear restrictions and stakeholder participation to be the five most efficient tools for Ecosystem-Based Fisheries Management (Fig. 12).

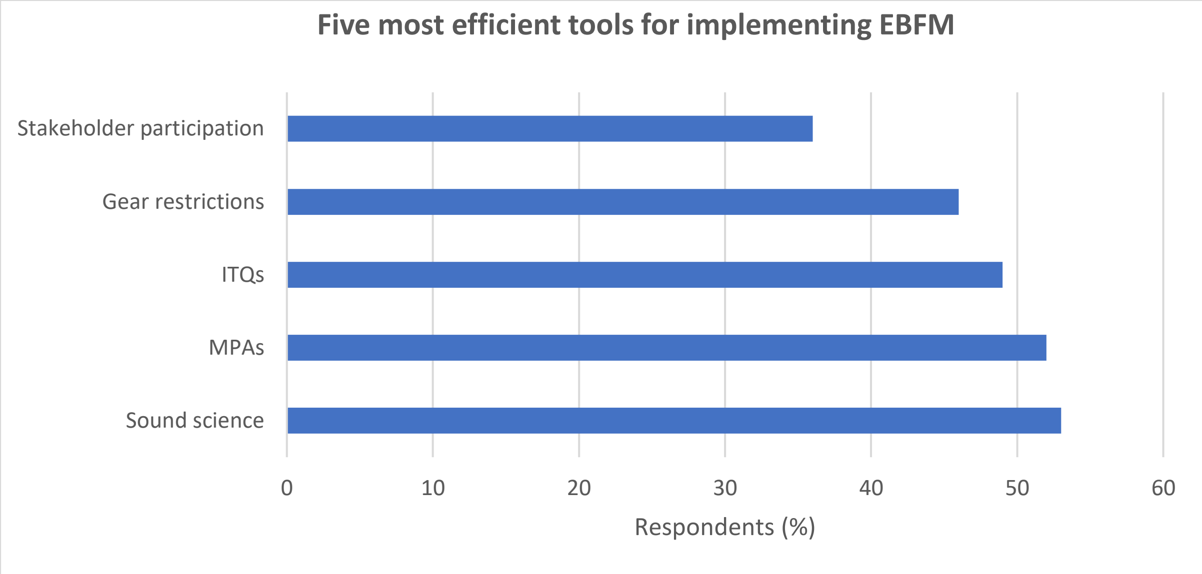


Figure 12: Participants' responses to the five most-efficient regulations for Ecosystem-Based Fisheries Management (n = 121). ITQs, individual transferable quotas.

Improvements needed to obtain and maintain sustainable fisheries

For the question on what type of organisation would be optimal for implementing EBFM, 83% believed that a mix of a top-down and bottom-up management is optimal (Appendix 4). When it came to what more is needed to sustain fisheries, 72% of all respondents answered they believe a stronger political will is needed to achieve successful ecosystem-based management (Fig. 13).

There was no significant difference among the responding groups regarding which improvements are needed to sustain fisheries ($G = 5.747$, $df = 20$, $p = 0.999$), with all groups identifying the same mix of factors. However, this congruence did hide some differences in detail. Amongst managers, a clear majority (79%) stated that stronger political will is needed. A majority of managers (60%) also said they think more enforcement is needed; this latter result is in sharp contrast to the 25% of fishers who felt the same way. Overall, 53% of the respondents believed that more science is needed in order to obtain and maintain sustainable fisheries (Fig. 13).

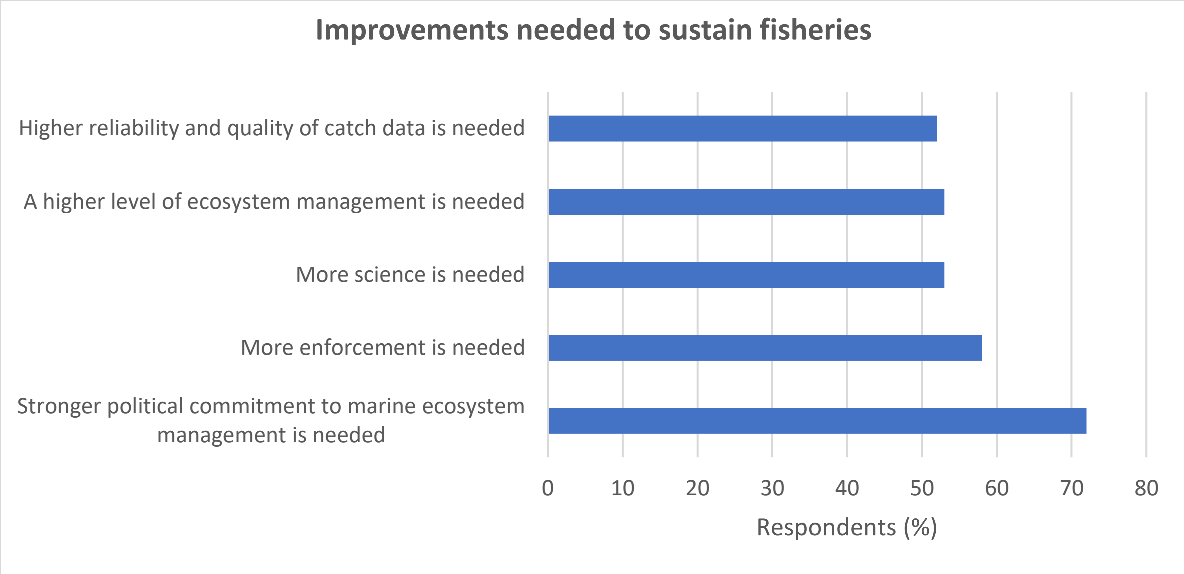


Figure 13: Improvements needed to obtain/maintain sustainable fisheries (n = 165).

The majority of the respondents were supportive of input controls, such as by-catch reduction devices, size limits, spawning and spatial closures, regional zoning, seasonal closures and gear restrictions (Fig. 14). The majority of the respondents also showed support for output controls, such as total allowable catch (86%), individual transferable catch (69%) and bag limits (69%) (Appendix 4).

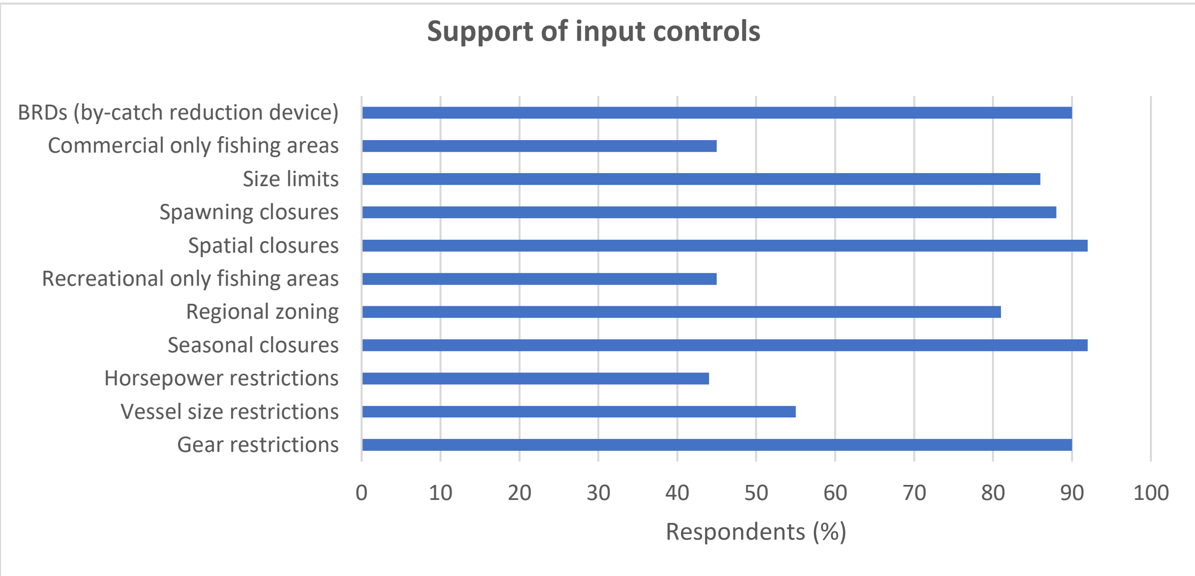


Figure 14: The level of support for several input controls shown by marine experts (n = 162).

When it came to monitoring and assessing stocks, Catch Per Unit Effort (CPUE) was the most common method used for measuring fish abundance (Fig. 15), although logbook data was considered a close second.

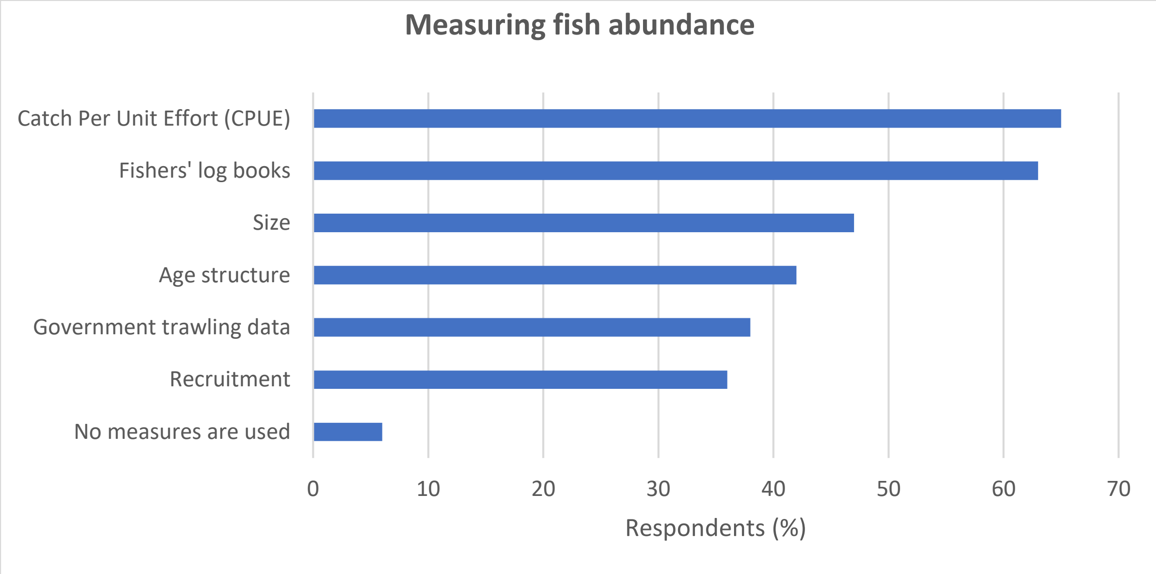


Figure 15: The prevalence of different approaches to measuring fish abundance.

Experts were asked to identify what they see as the main challenges to sustainable fisheries and what management tools would be generally useful for combatting challenges in fisheries (Table 3). Interestingly, while the challenges included things that are beyond the scope of fisheries management alone (e.g., land-based pollution or plastics), all of the suggested tools are classical fisheries management tools. When asked the question regarding why regulated fisheries are still faced with overexploitation, the highest ranking responses were: (1) the need for more scientific information; (2) existing science not being used to its fullest; and (3) a lack of political will. There was no significant difference to these three reasons among the responding groups ($G = 2.001$, $df = 10$, $p = 0.996$). The vast majority of all responding groups (regardless of background) said that the lack of political will is a major reason why regulated fisheries are still faced with overexploitation (Table 4).

Table 3: Ten main challenges and ten main tools for sustaining fisheries (n = 133).

Ten Fisheries Challenges	Ten Tools for Sustain Fisheries
Overfishing	Seasonal closures
Climate change	Total Allowable Catch (TAC)
Habitat destruction	Size limits
Pollution from land	Spatial closures (e.g., MPA)
Ecosystem shift	Ecosystem-Based Fisheries Management (EBFM)
Ocean acidification	Spawning closures
Plastics in the oceans	Mesh size
IUU fishing	Individual Transferable Quota (ITQ)
Coastal development	By-catch reduction device
Introduced species	Regional zoning

Table 4: Major reasons for why regulated fisheries are still faced with overexploitation.

	Managers	Policy Makers	Scientists	Fishers	NGOs
Not enough scientific information	72%	54%	78%	73%	80%
Scientific knowledge is not fully being used	64%	67%	53%	62%	20%
Lack of political will	93%	92%	74%	84%	80%

Socioeconomic situations affecting fisheries and marine systems

Forty-two percent of the respondents said fish as a protein source is not important for survival in their country, 7% said it was, and 23% considered fish vital for some regions (Appendix 4). However, when questioned on how important fishing is as a main source of income, 65% of the respondents said fishing is the major economic activity for a few regions, 42% said fishing is a vital source of income for some regions and 37% said that fishing is somewhat important as a main source of income for the country as a whole (Appendix 4). Regarding subsides, 52% of the respondents said that fisheries subsidies are available in their country, 34% said there are no subsidies and 14% did not know (Appendix 4). Of those who said there are subsidies in their country, 88% said they have fuel subsidies, 35% have employment subsidies, 26% have lower interest rates on bank loans and 15% said they have subsidies related to culture. Sixty-five percent of the respondents believed that subsidies contribute to overcapacity of the fishing industry (Fig. 16).

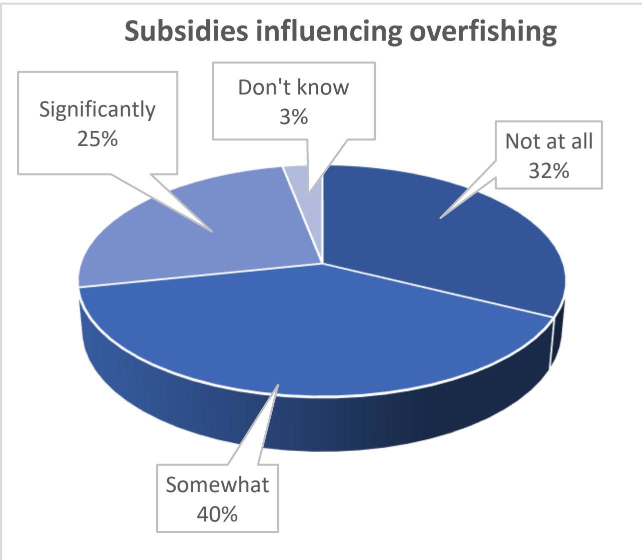


Figure 16: Respondents' belief regarding whether subsidies contribute to overcapacity of the fishing industry (n = 87).

There was particular support amongst the respondents for economic incentives, such as fishing access agreements and fishing vessel buy-backs by the government (Fig. 17).

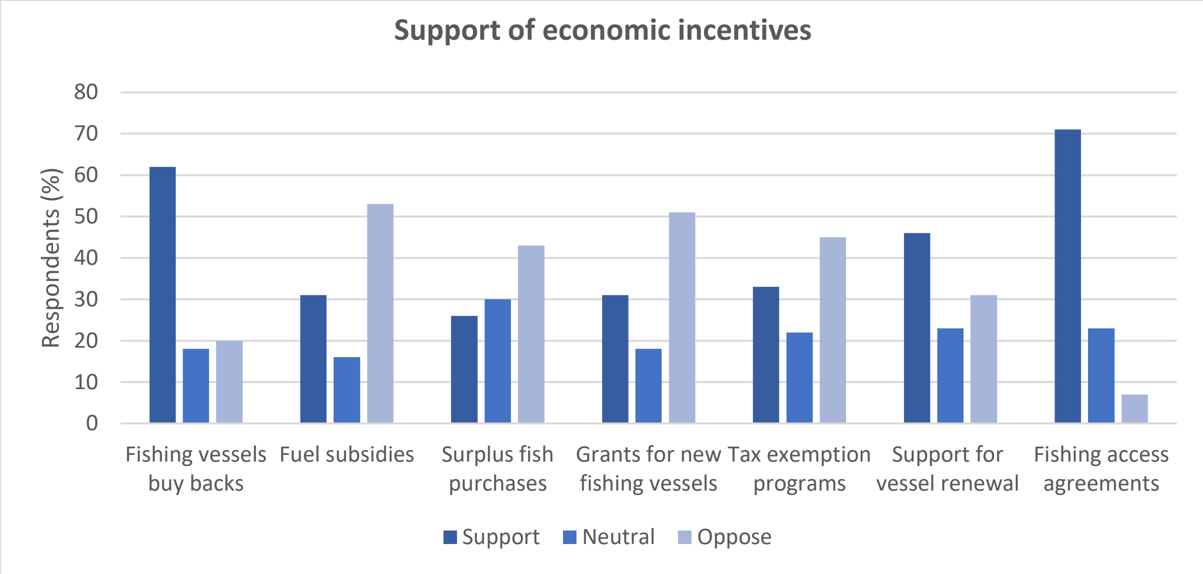


Figure 17: Experts showed large support for fishing vessel buy-back schemes and fishing access agreements (n = 168).

Fifty-one percent of the respondents were not able to estimate the cost of management for the fishery they work with (Appendix 4).

Discussion

Results from the survey demonstrate that the respondents have had extensive experience in the fisheries management process, including both science and management. The respondents had formal qualifications and/or experience; with 42% having Doctoral degrees, 28% Masters degrees and almost half of the respondents having senior or executive roles in fisheries. The coverage was also global, representing 34 nations in total. While we acknowledge the sample sizes were uneven, with more scientists answering than any of the other respondents, there was congruence in many results, suggesting that perceptions held by fisheries scientists and managers may not actually be that different. Indeed, in many cases, fishers also held similar attitudes, though there were some notable differences (e.g., on the need for additional enforcement). In following up on why it proves so hard to access the opinions of managers, let alone policy-makers (who were an even smaller respondent group), it became clear that they lack opportunities to gather and share information in the same way as provided by scientific conferences. Funding such travel is often hard to do. In improving the state of fisheries globally—sharing insights into what has and has not worked—it appears that there is a fundamental need for the creation of a fora, or a conduit, for information sharing amongst these managerial and policy groups.

Threats and challenges in sustaining fisheries

This analysis clearly confirmed that sustaining fisheries is a complex challenge, but the experts also offered their opinions as to how to combat the issues involved, which are generally consistent with the literature on how to sustainably manage fisheries (Nakatsuka 2017, Marshall et al. 2018). The respondents considered the 10 main threats to fisheries to be overfishing, climate change, habitat destruction, pollution, ecosystem shifts, IUU fishing, ocean acidification, costal development, land-based pollution and introduced species. These same threats were considered important at national and global scales. This shows that the threats and challenges to sustaining fisheries are similar around the world; a finding consistent with existing scientific literature (Smith et al. 2007, Fulton et al. 2014, Skern-Mauritzen et al. 2015, FAO 2016, Gullestad et al. 2017, Gianelli et al. 2018).

Management tools in sustaining fisheries

Although the analysis highlights an extensive range of challenges in achieving sustainable fisheries, it also shows that the respondents believe there are many existing tools for addressing these obstacles and supporting sustainable fishing. Just as the main challenges and threats to sustaining fisheries were viewed similarly around the world, so too the list of potential tools was consistent across respondents from differing backgrounds and nationalities. While overfishing was seen as a major threat to sustaining fisheries (nationally and globally), the majority of all responding groups said it is not a challenge to manage. Given concern over the magnitude of the problems facing "small scale" fisheries and the difficulties of achieving successful management in locations with few regulatory resources (Graham et al. 2013), this is a surprising response. However, this may be because the respondents primarily work in fisheries with a range of regulations in place, with compliance and enforcement mechanisms already implemented to combat this challenge and so they have directly experienced the management of overfishing. This result may highlight a tacit bias in the work—people working in less well-resourced fisheries are unlikely to have had the means to visit the

Congress where the survey was undertaken—and future follow-up on this work should endeavour to address this gap.

Tools identified as useful in sustaining fisheries included sound science, input controls (gear restrictions, seasonal closures, spatial closures, spawning closures, by-catch reduction device, size limits and regional zoning), output controls (bag limits, ITQs, Total Catch Limits (TACs)), a mixture of top-down and bottom-up organisation, stakeholder participation, fishing access agreements and fishing vessels buy-backs, effectively taking an integrated or ecosystem approach. In particular, the vast majority of all responding groups viewed good science, MPAs, ITQs, gear restrictions and stakeholder participation to be the five most efficient tools for Ecosystem-Based Fisheries Management. All of these tools are consistent with what have been recorded as good supporting tools for sustainable fisheries in other research (Scheffer et al. 2001, Christensen et al. 2004, Levin and Möllmann 2015, Skern-Mauritzen et al. 2015).

More of the respondents were satisfied than dissatisfied with the EBFM's planning and implementation processes. More were, however, neutral regarding the results of the EBFM, reflecting in part the complex nature of the EBFM process. Management tools might be put in place, but it may take a long time before any results are seen. These approaches may be introduced when the system has been overfished and shifted to a state where restoration may take a lengthy period (Nellemann et al. 2008, Bergmann et al. 2015, IMO 2017). More managers than any other responding group said they believed the EBFM implementation process was a success. About the same number of managers, policy-makers and scientists said they believed it was unsuccessful. Possibly, there were different expectations among the various responding groups, where the managers saw it as a success in itself that such a large management process had been adopted and implemented by the government in the first place; while the scientists may have been more cautious (neutral) because any biological success was yet to be seen. More managers and policy-makers said they were satisfied with the results of EBFM than the scientists and fishers, although all responding groups showed a cautious element to any success, the fishers more so than any other group. Again, the expectations are likely to differ among the various stakeholders, as implementing EBFM unavoidably involves trade-offs in meeting all biological, economic and social goals (Haward 2018), which will differ between the different groups.

Given the growing focus on the implications of a high level of marine pollution (Plagányi et al. 2004, Gascuel et al. 2016, ICES 2018), it might be surprising that only just over half of the respondents answered that they believe land-based pollution is a major threat to the world's fisheries and 46% said plastic is a major threat. This might be due to the fact that the survey was undertaken in 2012 when there was not as much scientific reporting on plastics in the ocean (Voss et al. 2016). It was particularly noteworthy though that, despite pollution and plastics being identified as threats, few, if any, of the suggested tools put forward are likely to have a significant role in combating these issues. This indicates that, while awareness of the issue is growing, focus is still on the classical threats and long-established tools.

Management constraints in using more science

Fisheries management in the majority of industrialised nations is said to be science or evidence-based, even if science-based advice is not always followed in the political process (Ballesteros et al. 2017). This analysis showed 'not using scientific knowledge to its fullest potential' to be the main constraint for effectively and efficiently implementing ecosystem-based fisheries management, together with: (1) a lack of compliance; (2) IUU still being a major global issue; and (3) political will.

The management of marine systems in general, and fisheries in particular, is highly complex and a story of information paucity. It is very difficult to estimate even the abundance of target species. In some regions, it is even difficult to precisely determine what has been extracted from the ocean, let alone the effects on dependent species or species not directly impacted by fishing (Leite et al. 2016). The reason why science is not being used to its fullest is interesting. Is it because of a disconnect of science and management? In Australia, having fisheries scientists work closely with but ultimately sit apart from the management agency has been a successful approach, as the participatory processes in place there allow for communication, while the 'distance' has helped increase trust in science and motivation of scientists by all stakeholders. In other regions, the organisational disconnect has led to barriers to information uptake. In these latter instances, because scientists belong to a separate organisation, they are treated more as a consultant and thereby not fully integrated in the management process, leading to critical communication failures. An example of this is where scientists from the International Council for the Exploration of the Sea (ICES) advise the Oslo Paris Commission (OSPAR), the Helsinki Commission, the Baltic Marine Environment Protection Commission (HELCOM), the North East Atlantic Fisheries Commission (NEAFC), the North Atlantic Salmon Conservation Organization (NASCO) and the European Commission (EC) (Elmgren et al. 2015). Yet, despite all of these channels, the decisions have still been largely political, leading to overfishing within the European Union (Gascuel et al. 2016, Fernandes et al. 2017). More recently, there have been significant efforts to reverse this, though it has only been patchily effective; the Mediterranean, in particular, still has a majority of its stocks in an overfished state (Froese et al. 2010, Vielmini et al. 2017).

An alternative example is found with the Commission for the Conservation for Antarctic Marine Living Resources (CCAMLR). CCAMLR has its scientific committee with its working groups fully integrated in the organisation advising the commission at the annual meetings. Many participants are a part of both the scientific commission and the commission (CCAMLR 2017, CCAMLR 2017, CCAMLR 2017). This science-based commitment to ecosystem-based management has, since 1982 (when CCAMLR was founded), contributed to the recovery of previous overfished stocks, and sustainable management of the Southern ocean ecosystems, including fisheries (CCAMLR 1980, Constable 2011).

A brief comment on cognitive inconsistencies

With the growing accessibility of literature regarding human cognition, it would be remiss of us not to note how the perceptions reported in this survey may be effected by common cognitive biases and fallacies (Cooke et al. 2013). We are not trained professionals in the field of psychology, so will not go into depth, but the results for IUU appear to be a stand out example of such biases in action. There is clear recognition that IUU is a problem, with almost complete consensus on this point across respondents. However, it appears that the perception of the magnitude of the problem is strongly influenced by an optimism bias (with far fewer respondents thinking it is a problem in their own fishery) and by biases to do with framing (it is seen as more of an issue when asked directly about IUU rather than in general bundled with other risks) and uncertainty (as the true magnitude of the problem is typically unknown and so may be discounted as a result). In addition, the fact that the suggested solutions for sustainable fisheries include a list of existing tools, many of which have been in use in fisheries for centuries, suggest that there may be a strong endowment effect, with experts sticking strongly to tools they are already heavily invested in without necessarily looking for new alternatives. This is worth additional research to verify. If confirmed, it would open up new research paths; if falsified, then it would reassure all stakeholders that we already have at hand all the tools we need to achieve sustainable fisheries.

Political will to match biological challenges

The survey showed that, despite implementation of EBFM and increased levels of input from science, industry and NGOs, sustaining fisheries remains a challenge. The main challenge when managing fisheries was said to be a lack of political will. We note that policy-makers represented just 7% of the respondents, and the issue of sustaining fisheries due to a lack of political will might have been viewed differently had there been more policy people participating in the survey. Indeed, knowledge brokers who span the science–policy interface caution that policy-makers can become frustrated with scientists who fail to appreciate the many sources of information and many pressures that must be navigated by policy-makers when making a single decision (Perrings et al. 2011, Lacey et al. 2018). Political advisers and politicians must also consider political, social, cultural and economic matters.

The challenge to managing fisheries ranked second by the respondents was a shortage in compliance and regulations, stock assessments and monitoring. This might not come as a surprise as there are high costs involved for scientific assessments and controlling regulations (Fairclough et al. 2014). In linking the top two challenges, the challenge found regarding the lack of compliance may reflect a lack of general political and social will to fund and implement required management controls (Cooke et al. 2013, Voss et al. 2016, Lu et al. 2017). Politicians may be more inclined to act on issues more important to the voters (who have concerns extending well beyond fisheries), and perhaps, at times, they do not either fully appreciate the seriousness of the marine issues or the need for long-term sustainable plans that span many election cycles.

However, what might not be high on the political agenda today may change with building public awareness, which in turn may demand better management of natural resources (Lu et al. 2017). The United Nations' Ocean Conference for implementation of Sustainable Development Goal 14 ('Conserve and sustainably use the oceans, seas and marine resources for the sustainable development') is an example. This conference was held in June 2017, with 193 nations making a commitment to a set of measures aiming to increase the resilience of ocean health. These pledges have been accompanied by over 1400 voluntary commitments. Together, these commitments can be seen as a global commitment (raised from increased scientific and public pressure) for politicians to better manage marine life. Given increased consciousness of environmental issues among the public since this survey was conducted(Cooke et al. 2013, Lu et al. 2017), it would be interesting to conduct a similar survey today to see if there is a perception of a stronger political will today to sustain fisheries.

Conclusions

This study reinforces the magnitude of the challenges in sustaining fisheries. It identified key issues underpinning the use of an ecosystem management approach, such as complexity, the high degree of connectivity, difficulties associated with observing ocean processes and monitoring flora and fauna. The fact that 99% of the respondents believed that IUU fishing still is a global problem and 65% estimated the global level of IUU fishing to be between 31 and 60% of the total catch worldwide is, naturally, a major concern. Tools identified as useful in sustaining fisheries included sound science, gear restrictions, seasonal closures, spatial closures, spawning closures, by-catch reduction device, size limits and regional zoning, bag limits, ITQs and TACs. The study indicated that the common position of the respondents is that the use of a mixture of top-down and bottom-up organisation and institutional forms is important to success, as is the importance of stakeholder participation. However, implementing these solutions will come with new challenges, especially when implementing them at scales aligning with the magnitude of participation in "small-scale" (often poorly resourced) fisheries in developing nations. The survey also highlighted the impact of fishing access agreements and fishing vessels buy-backs as tools to constrain effort. Again, these are things that may work more effectively for industrial than some artisanal fisheries.

This research illustrated a clear perception of a need for a higher political will and commitment to combat challenges, such as IUU fishing, habitat destruction and climate change, both nationally and globally. More research and long-term monitoring to assist managers in prioritization resources was also identified as a particularly important need. It was clear from the analysis that the widely held belief by those experts in charge of the world's fisheries that, to recover from overfishing and fisheries collapse (and to minimise the future risk of such events), scientific input must be matched with the same level of political commitment, including implementing science-based fisheries and conservation measures.

It is also worth noting that human cognition is not infallible. When asked directly about illegal, unreported and unregulated fishing, 99% of the respondents saw it as a global issue; however, when put against other challenges, close to 70% of the policy-makers and scientists believed that is not a major threat to national fisheries, despite the fact that almost 80% of the fishers said they think it is. This suggests that there is a gap in the discourse and management of IUU fishing that likely needs closer consideration or discussion.

This analysis showed that there is the strong perception that scientific knowledge is not being used to its fullest potential and that in turn is the main constraint for effectively and efficiently implementing ecosystem-based fisheries management. Is the challenge then a lack of political will only, or is this a reflection of the make-up of respondents: scientists frustrated with a perceived lack of political appreciation? Perhaps there is a greater need to establish science-management networks that meet regularly, to train a new generation of scientists who have direct industry and regulatory body experience (spending time in both as well as academia before completing their training), as well as a need for scientists to communicate science in a more pedagogical way?

Chapter 4: Consensus management in Antarctica's high seas – past success and current challenges

Abstract

The high seas surrounding Antarctica have a vast and diverse marine environment. Following its establishment in 1982, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has managed the ecosystems of the high seas of the Southern Ocean. CCAMLR pioneered the ecosystem approach to resource management, took action on the problem of sea bird by-catch, and has established measures to combat illegal unreported and unregulated (IUU) fishing. CCAMLR is seen as an example of best practice in managing marine resources in international waters. At the same time, CCAMLR's challenges arise in the balance between 'fishing' and 'conservation' interests; for example in the current debates over climate change and marine protected areas in the Southern Ocean. In each of these examples, CCAMLR's consensus-based decision-making process has been a central element in shaping outcomes. This paper considers CCAMLR's achievements in sustainable marine ecosystems and identifies emerging challenges.

Introduction

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has managed the marine living resources in the Southern Ocean for over 30 years. CCAMLR was innovative when it pioneered an ecosystem approach to marine resource management (Howard 1989, Basson et al. 1991) within the Convention on the Conservation of Antarctic Marine Living Resources). This Convention includes a focus on a precautionary approach and has an explicit focus on rebuilding exploited stocks. CCAMLR incorporates a consensus decision-making model that can provide challenges in the deliberations among the 25 CCAMLR Members (Haward et al. 2012). This challenge is most notable in the current debate over the implementation of a representative system of marine protected areas within the Convention Area. Nevertheless, the consensus-based management approach has seen CCAMLR successfully negotiate complex management issues in a forum where Members have differing interests; that is between states focused on marine resource extraction and others focused on marine resource and environmental conservation. It should be noted that this dichotomy is not absolute, with Members supporting CCAMLR's mandate to balance extraction with conservation.

Here we outline and assess CCAMLR's achievements and identify key challenges it faces currently in addressing its core objectives around sustainable marine ecological systems in the Antarctic. We argue that, notwithstanding these challenges, CCAMLR provides a model governance regime for contemporary marine resources management, and the lessons learned in the development of this regime have had broad application for other fisheries and regions (Willock et al. 2006).

International ocean governance and conservation of Antarctic marine life

The Southern Ocean, which represents about 10% of the Earth's surface, surrounds the Antarctic continent. Commercial fishing of krill and fish species in the Southern Ocean commenced in the late 1960s and early 1970s (Agnew 1997). Fishing in such distant and high latitude waters had been facilitated by industrialisation of fishing and developments in vessel design, catch processing, and in technological advancements in communication and navigation (Jackson et al. 2001). In the Southern Ocean, and elsewhere, industrialization has been associated with greater investment in fishing gear, higher competition, increased effort, and greater mobility, which together typically leads to increased fishing pressure, often followed by overfishing (Branch et al. 2010).

Increasing, and at that time unregulated, fishing of krill in the 1970s focused the attention of the Antarctic Treaty Consultative Parties. Concern was expressed that krill stocks could be over-exploited. Krill are recognised as a keystone species, acting as an energetic link between primary production and higher trophic layers (Suter 1991). In addition, in the 1970s and early 1980s several stocks of Antarctic finfish were heavily exploited as a result of limited controls on large scale commercial harvesting (Kock 1994).

These unsustainable fishing activities initiated the negotiations within Antarctic Treaty forums in 1978, in relation to Article IX '…preservation and conservation of living resources in Antarctica' over what was termed the rational use of marine resources. These discussions concluded with the adoption of the Convention at the Conference on the Conservation of Antarctic Marine Living Resources held in Canberra, Australia, 7–20 May 1980. The CAMLR Convention aimed to conserve Antarctic marine life in a high seas area covering some 32 million km^2 at 60^o S (Fig. 1) and it entered into force on 7 April 1982 (CCAMLR 1982).

To implement the Convention, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was established by international treaty in 1982, with its secretariat located in Hobart, Australia. The CAMLR Convention established a Scientific Committee to provide advice to the Commission, based on the best available science. While the Commission is the final decision-making body, Article IX (4) of the Convention states 'In exercising its functions … the Commission shall take full account of the recommendations and advice of the Scientific Committee.' Today CCAMLR has 25 acceding Members, including the European Union, with a further 11 countries as contracting parties to the convention. The 25 Members are represented both in the Commission and the Scientific Committee and both groups hold annual meetings, have the right to participate in deliberations, pay an annual membership fee, provide scientific research to the Commission's Scientific Committee, and may be involved in marine resource harvesting.

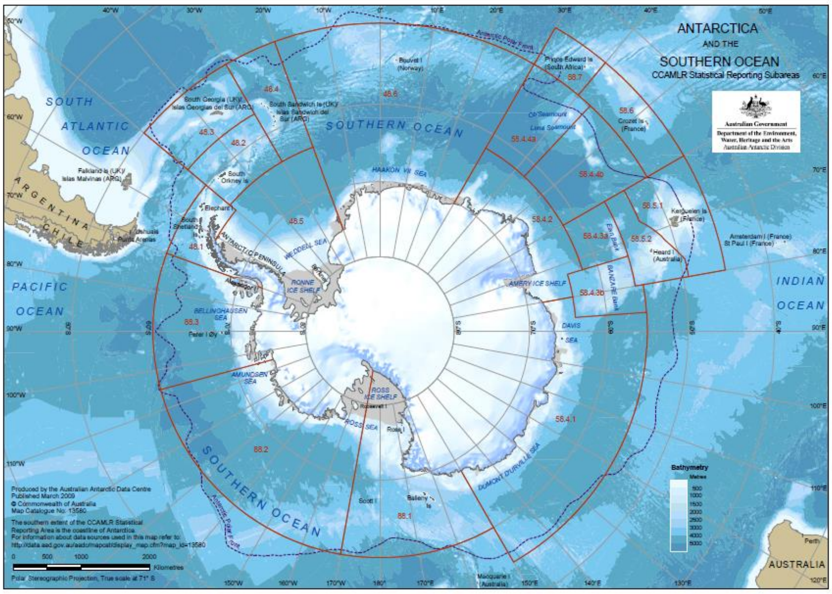


Figure 1: The CCAMLR Convention Area, divided into subareas. Map courtesy of the Australian Antarctic Division and is © Commonwealth of Australia (2009).

From its initiation, CCAMLR's main objective has been the 'maintenance of ecological relationships between harvested, dependent and related populations', utilising a new 'ecosystem approach' to fisheries management (CCAMLR 1982). It has been described as a conservation organisation with the attributes of a regional fisheries management organisation (Martin-Smith 2009). The Convention was the first international initiative to commit to monitoring a large marine ecosystem (Constable et al. 2000). In 1990 a moratorium on all finfish fishing was adopted by the Commission, aiming to conserve the remaining fish stocks (Bondareff 1990). The Convention excludes management of whales (which are managed under the International Convention for the Regulation of Whaling (1946) through the International Whaling Commission (IWC)), and seals (which are managed under the Convention for the Conservation of Antarctic Seals, CCAS (1972)).

Fisheries of the Southern Ocean

Fishers in CCAMLR's Convention Area currently target Patagonian toothfish (*Dissostichus eleginoides*), Antarctic toothfish (*Dissostichus mawsoni*), mackerel icefish (*Champsocephalus gunnari*) and Antarctic krill (*Euphausia superba*). The Scientific Committee and its subsidiary body, the Working Group on Fish Stock Assessment, annually assess the fisheries in the Convention and recommend TACs to the Commission. The catch limits are believed to be set at precautionary levels (Constable 2011, CCAMLR 2015).

The Krill fishery

The pressure on the krill stock has been low following the withdrawal of Soviet Union flagged krill vessels in the early 1990s (Kock 1994). In 2013 the Commission agreed on a krill catch limit of 620,000 tonnes (estimated to be 1% of the total krill biomass), with a reported catch of 217,357 tonnes at the end of the season (CCAMLR 2013). Recent expansion of markets (particularly for krill oil and aquaculture feed), with new fishing methods and harvesting techniques and new fishing grounds due to melting sea ice (Nicol et al. 2012), has attracted more vessels to this fishery. The possibility that Members may exert upward pressure on krill quotas in the future cannot be ruled out. Another challenge in managing krill is the sheer magnitude of the stock, with the biomass, currently estimated to be just under 400 million tonnes, may fall within the range of 60-420 million tonnes (CCAMLR 2015).

Toothfish

Both species of toothfish are believed to be fully exploited in the Convention Area and depleted in some parts of the Indian Ocean due to IUU (illegal, unreported and unregulated) fishing (Constable 2011). Being highly priced, toothfish is particularly vulnerable to IUU fishing as the market price for an illegal catch is believed to be around US$18/kg as compared to US$23/kg for legal catches.

Mackerel icefish

Mackerel icefish was heavily fished in the 1970s and 1980s, and in the early 1990s the fishery was closed out of concern over high annual variability in catches and continuous high exploitation (CCAMLR 2013). Reviewed annually, icefish is today harvested cautiously at South Georgia and *at* Heard and McDonald Islands. Overall icefish is believed to be fully exploited (Constable 2011).

CCAMLR and fisheries management

Following the entry into force of the CAMLR Convention, there have not been any documented collapses in fisheries managed by the Commission. Moreover, previously depleted stocks of toothfish have been rebuilt to the point that the Australian toothfish fishery received the Marine Stewardship Council eco-certification in 2012 and a ‘best choice’ label from the Monterey Bay Aquarium’s Seafood Watch program in 2013. This indicates that the management approaches and tools in place to date are considered to be in line with global best practice. Nevertheless past overfishing has left its stamp, with species such as the marbled rockcod (*Notothenia rossii*), a stock heavily fished prior to the establishment of the CAMLR Convention, showing no sign of recovery despite the fishery having been closed for over 30 years (Constable 2011).

Assessing CCAMLR’s achievements

CCAMLR’s management of fisheries links commitments to conservation with strong governance through conservation measures. In meeting these commitments CCAMLR is seen as a leader in regional fisheries organisations (Willock and Lack 2006). Four main factors stand out as contributing to these outcomes: a focus on science and decision-making using monitoring of indicator species; addressing IUU fishing; addressing incidental catch – particularly of seabirds; and last, but by no means the least significant, geopolitical factors.

Monitoring for management

CCAMLR’s commitment to the ecosystem-based approach to fisheries management demanded new tools and methods (Miller 2002). One criticism is that, despite such a commitment, it took almost a decade for the Commission to move to address the practical aspects of such an approach (Howard 1989). In 1989 CCAMLR established the CCAMLR Ecosystem Monitoring Program (CEMP) to consider the impact of fishing on dependent predator species, especially with regards to krill-dependent predators (Agnew 1997). As there is a large number of researchers from many different countries involved in data collection, the CEMP also facilitated the standardization of research methods. Further, research methods are regularly assessed and updated as necessary by CCAMLR's Working Group on Ecosystem Monitoring and Management, ensuring timely uptake of new research technologies such as those supporting remote sensing (e.g. satellite imagery, remote cameras) (CCAMLR 2007).

For many higher predators in the Southern Ocean (such as mammals, penguins, sea birds, fish and squid) krill is the primary source of food (Kock 2001). Krill's foundational role in the Antarctic marine food web and its accessibility for monitoring saw krill become a focus of monitoring by the CEMP (CCAMLR 2007). Other species monitored include the Adélie penguin (*Pygoscelis adeliae*), chinstrap penguin (*P. antarctica*), gentoo penguin (*P. papua*), macaroni penguin (*Eudyptes chrysolophus*), black-browed albatross (*Thallasarche melanophrys*), Antarctic petrel (*Thalassoica antarctica*), cape petrel (*Daption capense*), and Antarctic fur seal (*Arctocephalus gazella*) (CCAMLR 2007).

Addressing 'illegal fishing'

During its 34-year history, the Commission has governed the Convention Area by implementing binding Conservation Measures on its Members, supported by non-binding resolutions. The Conservation Measures and Resolutions address a range of areas including harvest controls, gear, vessel monitoring, fishing notifications, data reporting, landings, and by-catch (CCAMLR 2013).

IUU fishing occurs in high seas as well as in exclusive economic zones (EEZ), in waters of developing and developed nations, and by registered as well as by unregistered vessels (FAO 2013). The term IUU fishing was developed by CCAMLR, which was the first fishery organisation to explicitly address IUU fishing, with CCAMLR Members moving the item to the FAO and to wider attention (Edeson 1999, Haward and Vince 2008). Being a highly valued species, toothfish in the CCAMLR managed Convention Area has been the target for IUU fishing, and in the 1990s it was estimated (based on IUU vessel sightings by legal fishing vessels) that the actual catch was six times larger than what was reported by authorized vessels (CCAMLR 2013). Although still a concern, the IUU challenge is now controlled (Fig. 2), as the result of the adoption of a range of measures including surveillance, enforcement and market controls. These measures include IUU sighting reports; IUU vessel lists; recovery of IUU fishing gear; port and at-sea inspections; a Catch Documentation Scheme for toothfish (tracking catches from landing through the trade cycle); a compulsory Vessel Monitoring System on all vessels fishing in the CCAMLR-managed area; and support for Members surveillance and prosecution of IUU activities (CCAMLR 2013).

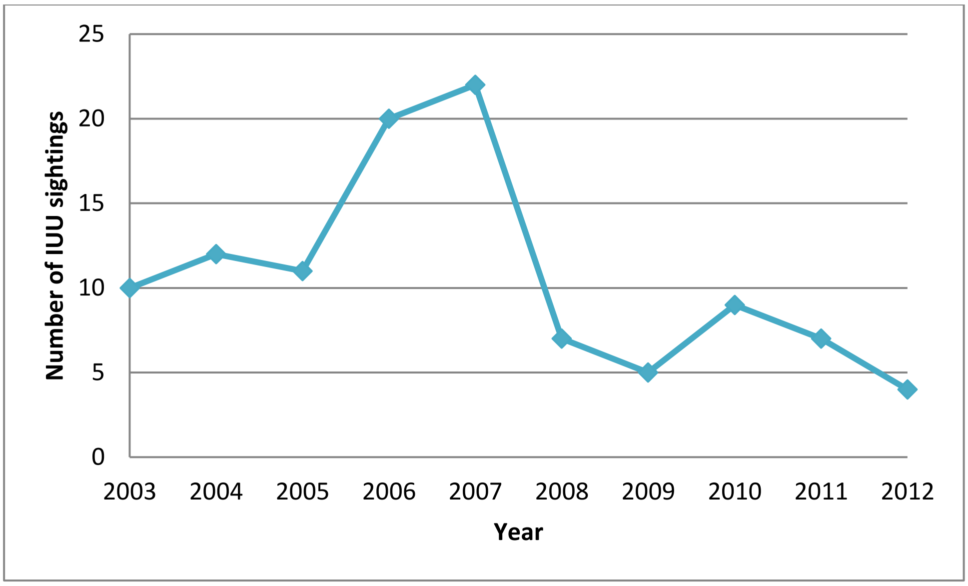


Figure 2: Number of IUU vessel sightings reported to CCAMLR (CCAMLR 2013).

There are seventeen vessels on CCAMLR's IUU list, which was established in 2003. Most of these vessels have been documented as fishing illegally several times and over many years (CCAMLR 2013). Based on the number of reported vessels, IUU fishing in the Convention Area has decreased, but it is clear that it is difficult to monitor and measure IUU fishing based on vessel sightings alone (the Secretariat stopped reporting these sightings in 2012). Using market based data and industry sourced information, COLTO (The Coalition for legal Toothfish Operators) estimated that the IUU catch for toothfish by six identified IUU vessels during 2014/2015 season was between 1264 and 1500 tonnes (COLTO 2015). In 2014-15 and 2015-16 action by Sea Shepherd Conservation drew attention to this small but persistent IUU activity targeting toothfish. A range of enforcement actions and international cooperation has targeted these six vessels performing small but persistent IUU fishing of toothfish.

Unreported catch by legal vessels is not included in any official statistics. For icefish and toothfish fisheries there is a requirement that an international observer is to be present for all fishing operations on all boats (i.e. 100% coverage), whilst the krill fishery requires 50% observer coverage, using either international or nationally appointed observers (CCAMLR 2014). In a break from standard practice within national EEZs, these observers are required by CCAMLR to report on scientific measures only (although Members may ask their observers to collect more data). The observers do not monitor the catches and are not required by CCAMLR to ensure that vessels comply with Conservation Measures (indeed they have no power to enforce compliance), nor are they actually required to report IUU catches.

While legal fishing vessels in the Convention Area are required to report any unidentified vessels, not all such vessels are reported (CCAMLR 2013). There is also potential misreporting of catch by legal operators. One example is that the Korean *Insung No. 7*, which was found to have breached two Conservation Measures; namely exceeding the regional catch by more than 300% (135.7t catch vs 40t limit) and catching 35 tonnes after the Master received notice they had exceeded the catch limit (CCAMLR 2011). When the Commission agreed to place this vessel on the IUU vessel list, Korea (a CCAMLR Member) refused to support the move, thereby permitting *Insung No. 7* to continue fishing in the Convention Area (CCAMLR 2011).

Another challenge is that there is differing capacity to deal with illegal activities of Members. Transparency International's Corruption Perceptions Index (how likely a country is to be corrupt) indicates that three of CCAMLR's Members rate as 'highly corrupt', 11 have a moderate rating and the remaining 11 are rated close to 'clean' (TransparencyInternational 2012). Countries where corruption is more or less accepted as part of business may be less able to follow Conservation Measures in practice even though they officially have agreed to them.

Addressing incidental catches of seabirds

In response to the increasingly documented by-catch of seabirds, CCAMLR adopted Conservation Measure, 29/X, in 1991 (now named Conservation Measure 25-02). The recorded seabird by-catch has since dropped from 6,600 birds in 1997 to close to zero in 2012 (Fig. 3) (SC-CAMLR 1997, SC-CAMLR 2012). This large decrease is due to a combination of new Conservation Measures, making it compulsory for fishing vessels to use streamer lines aimed at keeping birds away from the vessels, as well as using weighting of baited hooks to make hooks sink quickly so as not to attract attention from foraging birds (SC-CAMLR 2012). The Commission has also defined some initiatives on how fishers may manage marine debris so as not to harm seabirds. One such initiative is to process offal discharge on-board the vessels (Waugh et al. 2008).

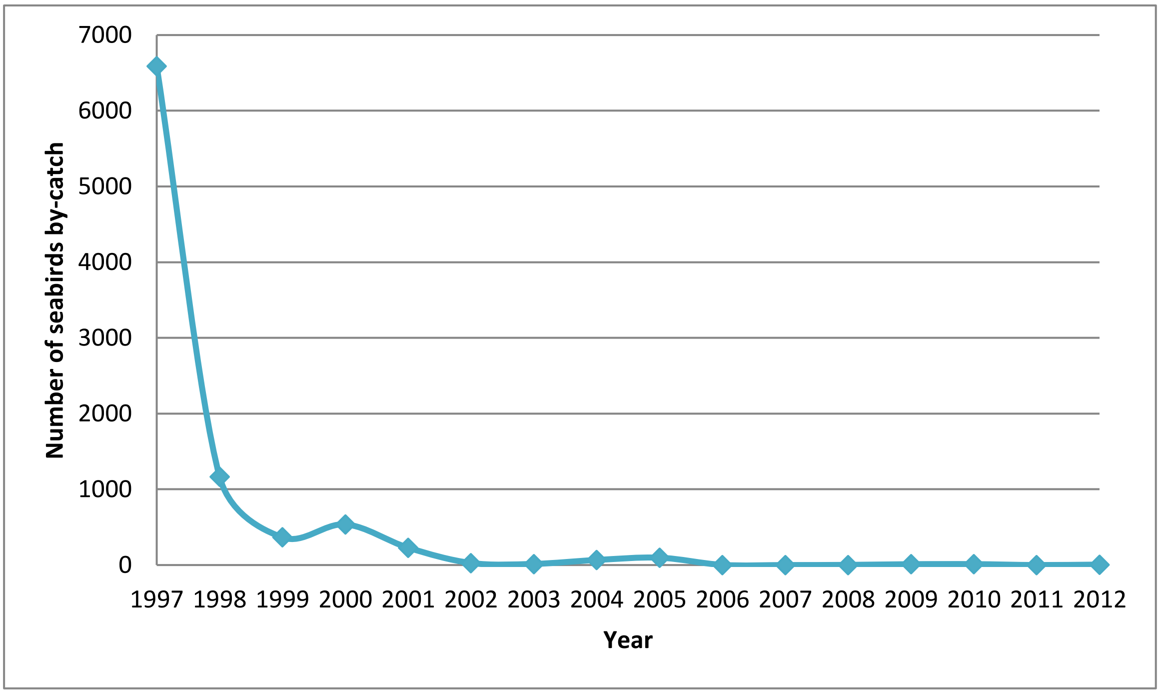


Fig 3: Incidental seabird by-catch mortality from demersal longline fishing for toothfish in the Convention Area (CCAMLR 2012).

While this reduction in seabird mortality is worthy of credit, incidental catch of seabirds may not have been completely eradicated, as it may still be occurring on IUU vessels. Work to restrict IUU fishing will therefore likely also help in reducing seabird mortality.

Geopolitical factors and consensus-based management

The remoteness of Antarctica, which makes it costly to fish in its waters, and the extreme weather conditions might be factors indirectly providing some protection to the Southern Ocean resources and associated ecosystems. Antarctica is the windiest and coldest place on earth, with wind gusts above 200 km/hr and the average annual temperature near the coast of -10°C, dropping to below -40°C in the winter (AAD 2002). Even though the CCAMLR fisheries are open all year around, extreme cold and wind in winter provide challenges for fishing. During the summer other challenges to operating at high latitudes arise from icebergs and sea ice.

International politics also play a major role in Southern Ocean management. Part of the CAMLR Convention Area is located within the Antarctic Treaty Area. The Antarctic Treaty states in its first article that '*Antarctica shall be used for peaceful purposes only*'. Further, Article IV of the Antarctic Treaty (replicated in the CAMLR Convention) removes territorial disputes or conflicts: *'No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force.'*

These particular geo-political conditions provide strong support for collaborative action. The differing interests amongst CCAMLR Members can, however, mean that consensus-based management is challenging, as every single Member has to agree to a proposal and Members do not have to forward a particular reason when disagreeing. This often time-consuming process has been criticised for hindering appropriate responses to conserve a constantly changing marine environment (Clark et al. 2001). Conservation Measures often include details that might take several years to negotiate and to adopt (Croxall et al. 2004). CCAMLR retains a strong normative commitment to the ecosystem approach yet it is valid to question the strength and robustness of this commitment in terms of fisheries management, the MPA, and climate change proposals (especially given the rapidity of climate related change).

Consensus in this very politically sensitive geographical area could be argued to now define the lowest common denominator rather than, as seen in the early days, working towards the highest achievement.

What is next? Some current challenges

The Southern Ocean is one of the fastest changing regions globally, with average temperatures having already risen by close to 1°C (Bindoff et al. 2013, Stocker et al. 2014). To cope with this degree of change Antarctic ecosystems will need to be exceptionally resilient (IPCC 2014). Conserving living marine resources is a highly complex task where the effects of climate change needs to be mitigated. Another challenge involves controlling fishing pressure (including IUU fishing) and its impact on the ecosystem, which must continue to be the focus of attention to provide Antarctic ecosystems with as much adaptive capacity as possible.

How many fish are there?

Governing fisheries using the ecosystem-based approach demands that fishing does not supress any stocks within the ecosystem to levels that reduce survival or reproductive success. Despite the Commission's largely positive fisheries record in recent years, challenges remain. Therefore, and in accordance with Article II of the Convention, a core task for CCAMLR is to estimate the biomass effects from fishing pressure within each of the statistical areas, subareas and divisions of the Convention Area. Once these estimations have been identified sustainable TACs can be set. Bioenergetics models used to reach those estimations of total prey consumption ask for data on the number of individuals in a population, the energetic demands of each individual and the diet composition (Boyd 2002, Forcada et al. 2009).

The Commission aims to set precautionary catch limits using the stochastic generalised yield model (GYM) (De la Mare et al. 1998), which only models a single species. Another issue using the GYM is that the estimations of pre-exploitation biomass and the annual TACs do not incorporate the 10-fold inter-annual variability of krill abundance and biomass (Flores et al. 2012), leaving no validation system and thereby no mechanism to compensate for unexpected low recruitment due to unknown environmental variables, perhaps including climate change. These challenges have been recognised by the Commission and, for krill, integrated assessment models were first implemented in 2011 (CCAMLR 2011). This was again brought up at a CCAMLR symposium in Chile 2015, suggesting that more focus on the links of the Antarctic food webs needs to be considered when setting TACs so to move away from single species stock assessment (CCAMLR 2015). However, for the Commission to adopt a multi species modelling approach to further implement a full EBFM approach all Members would need to agree to do so. Even without taking such a step, the variables in the GYM include recruitment variability, growth and mortality but not how these variables might be affected by climate change or ENSO events (Flores et al. 2012).

It is not as if CCAMLR does not recognise its challenges. At the CCAMLR symposium in Chile 2015 some Members proposed that to take the ecosystem-based management approach further, work on whole ecosystem relationships would need to be undertaken as this is essentially absent from CCAMLR's work today (CCAMLR 2015). At the Symposium it was further noted that CCAMLR should consider ways to achieve a robust management framework for CCAMLR high seas fisheries, including the use of multi-year management plans and a revision of the principles and procedures for new and exploratory fisheries (CCAMLR 2015).

Questions have also arisen around monitoring methods. The Southern Ocean is a very challenging environment in which to work, and new sustainable effective monitoring methods are always being sought (e.g. satellite counts of penguin colonies) (Kock 2001). This has seen collaboration with fishing operators as a means of collecting information required for stock assessments. To estimate the abundance of toothfish, CCAMLR uses a capture-recapture method, where fishers during their fishing excursions are encouraged to tag and release, and to report on all recaptures (CCAMLR 2013). While this can be considered a sensible means of getting extra information it has been noted that it is insufficient by itself for setting sustainable Total Allowable Catches (TACs) (CCAMLR 2012).

The Working Group on Fish Stock Assessment acknowledges that there was a vast difference in the amount of tags released and recovered among the vessels, and suggests that training of fishers and scientific observers could be a solution (CCAMLR 2013). In the Fishery Report from 2013, it was acknowledged there are some key uncertainties about the stock assessment and in the SPMs [Spatial Population Models] of Antarctic toothfish (*D.mawsoni*), including knowledge in movement patterns associated with spawning, developing toothfish distribution and abundance information in areas closed to fishing. Some suggestions regarding how to address these issues have been considered (CCAMLR 2013). Moreover, simulations have suggested that *Dissostichus eleginoides* (Patagonian toothfish) has experienced varied levels of overfishing, and research catches show that it could take decades for depleted stocks to recover, even when the fishery is closed (Welsford 2011). These simulations also showed that even small levels of research catch can delay the recovery of the toothfish stock significantly.

As noted much of the current management practice is still primarily focussed on single species management. While work is being done on integrated ecosystem models this it is not always clear that this work addressed into the commission's decision making process (Abrams 2014). Nonetheless, CCAMLR's precautionary approach, its regular monitoring programs and data analysis provide robust fisheries governance (Hanchet et al. 2015), especially in comparison with the management of other high seas fisheries.

Monitoring 32 million km2 of international waters

Despite representing a systematically collected dataset covering almost 30 years, the CCAMLR Ecosystem Monitoring Program (CEMP) covers a small number of sites and with no mechanism to translate the monitoring results into Conservation Measures or other management strategies (Constable 2011). This, and the lack of a feedback management system based on these variables has been recognised by the Commission (CCAMLR 2011) and it would be encouraging to see greater spatial coverage in Members monitoring programs, with varying temporal and spatial scales. The vast amount of rather detailed data needed to set ecosystem-based TAC is a demanding task. To fully achieve EBFM, CCAMLR would need to address the temporal and spatial indifferences within CEMP as the length of foraging trips and breeding success may be affected by weather conditions, food availability and anthropogenic stressors such as fishing. CEMP would also need to monitor larger areas and include more detailed data of the Southern Ocean. A monumental (and at present likely infeasible) task given current resource and technology constraints.

Given krill's potential sensitivity to climate change induced environmental shifts (discussed further below), there is a recognised need to incorporate short and long term aspects of climate change effects on the abundance of krill when setting TACs; increase the research effort to more sites; and find a way to feed the information from this kind research into a more adaptive ecosystem based management system, which could in turn help improve the monitoring and the resilience of Antarctic ecosystems.

The establishment of marine protected areas

In 2005 CCAMLR committed to progress work towards a representative system of MPAs within the Convention Area by 2012. One example of the challenge with consensus-based management is the Commission's difficulty in adopting proposed new Conservation Measures on the establishment of Marine Protected Areas (MPAs) in the Convention Area. Establishing MPAs in the Convention Area is seen to support the Commission's broad mandate to rebuild fish stocks and they could also serve as reference areas for monitoring anthropogenic impacts (e.g. harvesting and climate change) occurring in the Southern Ocean.

CCAMLR has consistently addressed the marine environment as part of its focus on its ecosystem approach (Martin-Smith 2009). The commission responded to international concern over protecting vulnerable marine ecosystems (VMEs) through development of precautionary practices and then specific conservation measures for designation and management of VMEs within the CCAMLR Area (Martin-Smith 2009).

In 2009, the Commission implemented an MPA by making the southern Atlantic on the South Orkney southern shelf an MPA (proposed by the UK), covering 94,000 km^2. In 2011 CCAMLR adopted Conservation Measure 91-04 (CM 91-04) 'General framework for the establishment of CCAMLR Marine Protected Areas'. Proposals to implement MPAs in east Antarctica and the Ross Sea were first proposed in 2012. Five Commission meetings later (including a special meeting in Bremerhaven, Germany, in 2013) they have not yet been adopted. The original MPA proposal off the Antarctic Peninsula submitted by the EU and the UK in 2012, aiming to protect newly exposed habitats due to the collapse of ice shelves, was withdrawn during the same meeting through lack of support. In an attempt to approve the attractiveness of a Ross Sea MPA, New Zealand and the US amalgamated their proposals for the region (also at the Commission meeting in 2012), creating the Ross Sea Region MPA (RSRMPA) proposal. This proposal covers 1.57 million km^2, with over 1 million km^2 as a no-take. It was unsuccessful in 2012 and was again presented at the 2015 Commission meeting. The East Antarctic Region MPA (EARMPA) proposal submitted jointly by Australia, the EU and France currently represents 946,998 km2. During the 2015 Scientific Committee meeting a new MPA proposal, the Weddell Sea MPA, was presented for consideration by Germany. However, when the commission in 2016 adopted the measure to establish the world's largest MPA it proved that the consensus-based management model can still deliver positive and productive outcomes (CCAMLR 2016). At the time of writing discussions are ongoing around the surviving MPA proposals.

Conservation Measure (CM) 91-04 was adopted in 2011 in accordance with the Convention (Article IX), to provide a framework for the establishment of MPAs in the Convention Area, stating that '*This Conservation Measure and any other CCAMLR Conservation Measures relevant to CCAMLR MPAs shall be adopted and implemented consistent with international law, including as reflected in the United Nations Convention on the Law of the Sea*', and '*CCAMLR MPAs shall be established on the basis of the best available scientific evidence, and shall contribute, taking full consideration of Article II of the CAMLR Convention where conservation includes rational use'* (CCAMLR 2011). During the 2014 and 2015 meetings Japan submitted a proposal to standardise a procedure to establish MPAs. This was opposed by several Members at both meetings on the basis that CM 91-04 includes substantial and adequate details for the creation of an MPA proposal (CCAMLR 2014, CCAMLR 2015). Should Japan's proposal, if presented again, be passed by the Commission it could further delay any MPA implementation as 1) the content of the standardised procedure would need to be defined and then agreed on by all Members, and 2) the already existing MPA proposals would have to be rewritten with potentially more (and new) information required. It could thereby be seen as a strategy to delay MPA measures by Members more interested in fishing than conservation, rather than a genuine effort to secure a procedure for implementing them.

This failure to reach consensus on the establishment of MPAs in the Convention Area could be interpreted as damaging CCAMLR's reputation and being the result of vested interests and concerns of particular Members related to access to fishery resources. This shows that consensus decision-making can create delays and additional challenges, possibly leading to delegates deciding against presenting some proposals believing consensus is unlikely. Other delegates observe, however, that the consensus process holds everyone accountable to the decisions made (CCAMLR 2005) and any agreed action is typically successfully implemented (Pomeroy 2001). This means that action on new CMs calls for considered and lengthy diplomatic negotiations to gain support from Members (any of whom may choose to block a proposal). This is because measures adopted by the Commission not only guide the future of Antarctic marine ecosystems, but also affect a Member's economic, social and political interests. The MPA proposal currently being developed by Germany for the Weddell Sea is an area of high interest to krill fishers (Gutt et al. 1994). It will be interesting to see whether additional MPA proposal(s) will facilitate the stated intention by the Commission to implement MPAs, or lead to deadlock through failure to gain consensus.

Discussion over establishing MPAs in the Convention Area has occurred for more than ten years now. It should be recognised that a failure to reach international consensus does not preclude nations acting in their own territories. For example, MPAs have already been implemented in claimed Antarctic territories: in 2002 Australia created a 71,200 km^2 Marine Reserve off the Heard Island and McDonald Islands Territory (extended in 2014); South Africa established an MPA in the Southern Ocean in 2009 in their EEZ, surrounding Prince Edward and Marion Islands 200 kilometres south of South Africa, covering 180,633km^2; France established MPAs off the Crozet (6,650km^2) and Kerguelen (6,000km^2) Islands in 2006; and in 2012 the UK implemented the largest (at the time) MPA in the world in South Georgia and Sandwich Island covering 1,070,000km^2.

Adapting to climate change

The Southern Ocean plays a vital role in the uptake of anthropogenic carbon dioxide, absorbing nearly half of the world's anthropogenic CO_2 emissions (Fraser 2007). The waters of the Antarctic Circumpolar Current, the largest current on Earth, surrounds the Antarctic continent and it is this water that has warmed, on average, more than any other part of the global ocean (Gille 2002, Meredith et al. 2005, IPCC 2014). The Southern Ocean is a region undergoing rapid environmental change and variability, with extreme patchiness in ice contraction, growth and seasonal dynamics (Dinniman et al. 2007). In the Antarctic and Southern Ocean climate change is impacting a number of areas, especially the Antarctic Peninsula, with evidence that 87% of the glaciers on the Antarctic Peninsula have retreated in recent decades (Trathan 2012). This, together with the collapse of ice shelves/ice tongues, can have significant implications for ice dependent species. For example, krill is dependent on sea ice during all its life stages. In addition, the duration, areal extent and thickness of ice are ecological parameters which have major implications for the reproduction and survival of krill, and thus the many marine species dependent on krill as food (Marschall 1988, Flores et al. 2012). Moreover, the increased accessibility of areas that now have reduced ice cover can lead to new areas and species being exposed to fishing with no conservation measures in place to protect them (Trathan et al. 2013).

Another challenge to the ecosystems in the Southern Ocean is ocean acidification (OA) (Doney et al. 2009). Driven by the absorption of excess atmospheric carbon, oceanic waters are becoming more acidic, with aragonite saturation already approaching corrosive levels for unprotected calcifiers in the Southern Ocean (Bednaršek et al. 2012, Dudeney et al. 2012). Although not all taxa are equally vulnerable, some pteropods (e.g. *Limacina helicina Antarctica*) found in the Southern Ocean are already show shell pitting, highlighting their susceptibility to acidification (Bednaršek et al. 2012, Seibel et al. 2012).

Individually, ocean acidification and climate driven changes in temperature present challenges to Antarctic fauna and flora, but it may be the cumulative effects of their combined change which is most telling. Before the direction shifts of climate change the Southern Ocean could be considered a relative stable (if somewhat extreme) environment and so species inhabiting it may not be able to cope with the degree of change and variability they will face under the combined pressures of climate change and ocean acidification. Between the warmest and the coldest habitats in the Convention Area there is a difference of only about 7^{o}C and krill, therefore, has not needed to adapt to high variability in temperature changes. This means krill has a low tolerance to temperature change. and research shows, that even a small change of 1-2^{o}C, can have a fundamental impact on krill recruitment, distribution, behaviour and other physiological performances (Mackey et al. 2012). In addition, laboratory experiments have shown that the level of acidification forecast could halt embryonic development of krill (Kawaguchi et al. 2011). For other crustaceans (in their natural environment) an increase in OA has been seen to affect growth, survival and recruitment as a result of diffusion of CO_2 across the gills (Orr et al. 2005, Whiteley 2011). Ocean acidification may also negatively affect the production of new exoskeleton, a process that takes place throughout a krill's life, and thereby jeopardize survival (Flores et al. 2012). Consequently, the combined effects of climate shifts and OA could see all aspects of krill life history under attack, ultimately potentially leading to a reduction in the importance of krill to southern ocean ecosystems (Constable et al. 2014). This could have profound implications for Southern Ocean ecosystems, because changes to krill abundance can have cascading effects through much of the Antarctic food web (Nicol et al. 2008).

One example of change to the ecosystem due to climate change that is already evident is on the western side of the Antarctic Peninsula, which has experienced the fastest rates of climate change recorded anywhere on the planet over the past 35 years (Holbrook et al. 2009, Montes-Hugo et al. 2009, Trathan et al. 2013). Research shows that this warming of the ocean has coincided with a decline in krill stocks and phytoplankton in the entire Atlantic sector of the Southern Ocean (Flores et al. 2012). The documented decrease in sea ice cover (Montes-Hugo et al. 2009) has also caused the decline in the ice dependent Adélie penguin, which has moved southwards (Ducklow et al. 2007).

Apart from climate change, climate anomalies such as El Niño Southern Oscillation (ENSO) and the Southern Annular Mode may further induce stress on the Antarctic ecosystems affecting, for example, recruitment and survival of Antarctic marine species (Carleton 1988, Holbrook et al. 2009).

CCAMLR members have responded to these emerging issues. During the Commission meeting in 2015 EU proposed special protection for areas that affected by retreating sea ice or iceberg collapse around the Antarctic Peninsula. The EU also presented a proposal to limit coastal krill fishing during penguins and seals breeding periods. Norway and the UK proposed a non-binding resolution on the inclusion of relevant views on climate change in all scientific documents that contributed to CCAMLRs work. None of these three proposals were adopted by the Commission. A proposal to appoint an intercessional task force to consider climate change in a CCAMLR perspective, was, however, adopted (CCAMLR 2015).

There was a resolution adopted by CCAMLR in 2009 to consider the effects of climate change on Southern Ocean ecosystems (CCAMLR 2009). Given CCAMLR's history of leading the introduction of the ecosystem approach to management, it may come as a surprise that of CCAMLR's five scientific working groups none is specifically related to climate. The Commission has not as yet adopted a climate change adaptation plan, as seen for example in the plans and strategies for the Great Barrier Reef in Australia (Great Barrier Reef Marine Park 2012), the Arctic (PAME 2015) and the US fisheries (Jason S. Link 2015).

The changing face of CCAMLR

It is not only the biophysical side of the Antarctic waters that is dynamic. CCAMLR is periodically reviewed and the Performance Review of 2008 reflected that when CCAMLR was established, less than 40% of its Members were fishing nations, compared with a majority today. As a result, Members' delegations include officials from Fisheries Ministries rather than from Ministries of Foreign Affairs or from Ministries of Environmental Protection (CCAMLR 2008). Co-management in fisheries has been shown to foster successful management (Berkes 1989, Pomeroy et al. 1997, Pinkerton 2011), but issues arise over the direct or indirect influence of fishing companies participating during the Commission's annual meetings (Bartley 2012).

As the Scientific Committee is charged with presenting the best science available as the basis for its advice to the Commission, the scientific work undertaken by Members is of major importance. The CCAMLR Performance Review identified issues concerned with the science that contributes to management, raising concerns that only a minority of Members regularly submit scientific papers or are involved in regular scientific expeditions collecting data for the benefit of conserving wildlife (CCAMLR 2008). Australia and the UK together account for 33% of the Member papers submitted to both the Commission and the Scientific Committee (Bartley 2012). Adding the US papers, these three countries provide 54% of the total papers submitted over the last 30 years. Other active Members include Chile, France, New Zealand, Russia and South Africa (Bartley 2012). This highlights that the original CCAMLR Members have a significantly higher commitment to providing scientific findings and adopting Conservation Measures than those Members that joined at a later stage. A similar trend has been observed within the Antarctic Treaty (Dudeney and Walton 2012). Interestingly, Korea, Norway, Poland, Spain and Uruguay who are among the most active fishing Members, have submitted less than 6% of the papers (Bartley 2012). This skew in participation may reflect differing capacities to execute science in such extreme conditions, but may also reflect differing priorities (e.g. in fishing, conservation, or a mix of the two) (Bartley 2012). This is not a new challenge. Research has shown that Members opposing submission of routine data are also those who oppose the adoption of Conservation Measures by arguing there is not sufficient data to support such a measure (Howard 1989).

Conclusions

There are more than 10,000 species in the Southern Ocean, and managing its ecosystems involves considering a large number of variables that may be changing at a fast rate. CCAMLR is globally acknowledged for its work on ecosystem-based management in the high seas surrounding Antarctica. CCAMLR's work over 34 years highlights the range of challenges in managing the Southern Ocean using the ecosystem approach. Differing priorities and interests among members ensure that it will continue to be a lively and dynamic (and on occasions frustrating) exercise. This process is unfortunately unlikely to get easier as the commission faces increasing challenges from the impacts and influence of climate change, ocean acidification and potentially increased fishing pressure on the region.

Shifts in species abundance and distribution are evident (Trathan et al. 2013). Concern over the cumulative stressors of fishing, climate change, ocean acidification and UV radiation will impact on the abundance of krill and thereby the whole food web have been expressed by several scientists (Seibel et al. 2003, Moline et al. 2004, Orr et al. 2005, Dahms et al. 2011, Kawaguchi et al. 2011). CCAMLR's future successes will be measured by its ability to respond to these stressors.

An ecosystem approach relies on provision of supporting data to ensure appropriate indicators can detect changes due to fishing (Fulton et al. 2005). It is likely that the effect of fishing pressure on seabirds may not have been detected were it not for several seabirds being indicator species in CEMP. That the impact of fishing on seabirds was recognised and CCAMLR's Members acted, endorsing Conservation Measures to mitigate incidental mortality of seabird bycatch, is a CCAMLR success story. The decrease in IUU fishing is also an example of CCAMLR's ability to effect change. Ongoing vigilance is required, however, with continued measures to combat illegal fishing in the waters surrounding Antarctica vital for sustainable marine environments.

CCAMLR is rightly seen as a leader in marine resources conservation. It does face ongoing challenges in fulfilling its mandate to ensure conservation/rational use of Antarctic marine resources. Although there are many positives with a consensus-based management approach, it is also a risky way to govern large, highly complex and rapidly changing environmental processes, particularly where it is well known that climate change is already impacting the Southern Ocean. Failure to gain agreement on the implementation of MPAs during five Commission meetings could be seen as a warning sign that the organisation's overall commitment to marine conservation is facing significant challenge, or it could be a manifestation of the time consuming processes that are a part of international politics and governance. However, when the commission adopted the measure to establish the world's largest MPA in 2016, CCAMLR proved that the consensus-based management model can still deliver positive and productive outcomes.

On the horizon there are also some increasing regional challenges, apart from rational use, conservation and climate change, including Members' claims to the continental shelf and sovereignty rights over sea bed resources.

Chapter 5: Conclusions - key lessons in sustaining fisheries

Sustaining marine ecosystems and fisheries is high on the global science and management agenda (CBD 2000, Levin and Möllmann 2015, Leite and Pita 2016, Ballesteros et al. 2017, FAO 2018). Ongoing exploitation of marine resources (Berkes et al. 2006, Kiuru et al. 2014) and other anthropogenic effects continue to impact on and effect changes to coastal and other marine environments (Jennings et al. 1998, Halpern 2008, Bergmann et al. 2015, Willsteed et al. 2017). With an increasing population and per capita wealth, global demand for protein, including fish, continues to rise (FAO 2018). At the same time there has been pressure from scientists and the public in general to better manage natural resources, including fisheries (Pikitch 2004, FAO 2016, FAO 2017, FAO 2018). This research has focused on an interdisciplinary and a holistic approach to consider biological, environmental, governance, economic and social pressures on fisheries.

The aim of this thesis was to provide insights into the structure of fisheries as socioecological systems with a view to identifying factors that contribute to a) fishery depletion and fishery collapse, and b) sustainable fisheries. Understanding what distinguishes well managed fisheries from those struggling (or failing) to achieve sustainability is a key desire of fisheries scientists and managers the world over (Swan et al. 2005, Hilborn 2007, Stephenson et al. 2018).

Unfortunately, no clear-cut directions exist, despite a lot of effort by scientists and managers to determine them (Melnychuk et al. 2017, Cisneros-Montemayor et al. 2018), usually by attempting to identify criteria that indicate an *a priori* warning to fisheries that are prone to collapse. The research reported in this thesis aimed to identify variables and criteria, alone or in combination, that could indicate whether a fishery is likely to collapse, to be over exploited, or conversely, be utilised sustainably. The overall research question underpinning this research was: Is there evidence that ecological, socioeconomic, or governance properties, alone or in combination, facilitate achievement or loss of fishery sustainability?

The research adopted an interdisciplinary approach to the question. It explored the interaction between a range of variables considered to impact stock abundance, namely biology, environment, social conditions, and economic, industry, governance and management variables. The research moved from a broad based global assessment to a survey of fisheries experts to a focused case study of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) to examine the efficacy of managing the high seas in the Southern Ocean. It drew widely on experience gathered from around the world and explicitly focused on three analyses involving;

1) analysis of six variables and 51 associated criteria in 21 fisheries across 11 nations, the EU and the high seas, investigating the connections among the biological, environmental, socioeconomic, industry, governance, and management variables (individually and in combination) that affect fishery sustainability;

2) expert knowledge and experience of 188 marine experts from 34 nations to understand the main challenges in managing fisheries and ecosystems, and to identify the main tools to combat these challenges; and
3) a focused case study of the efficacy of managing the high seas in the Southern Ocean through the 25 nations of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR).

One strength of the approach was to recognise and utilise the many faceted elements that influence fisheries sustainability. Factors contributing to sustainability were examined through an objective analysis of fishery characteristics, a survey of experts to see if they appreciate what these factors are (and any barriers that may prevent acting on that knowledge), and then an in-depth analysis of a specific case study.

The combined results of the three analyses showed a clear separation between collapsed and sustainable fisheries, and identified both some major challenges for fisheries management, and management tools proven to help sustain fisheries. The findings were similar to those of Costello et al. (2016) in the sense that applying science-based management tools to fisheries has the potential to recover stocks as well as to generate increased abundance of fishes and achieve maximum economic yield (Costello et al. 2016, Melnychuk et al. 2017).

Together the research underpinning this thesis showed that, among other things, many aspects of a fishery need to be considered to engender sustainability, including biological, environmental, governance, management, economic and social pressures on fisheries. Each component of the analysis aimed to expand on previous and contemporaneous efforts to find guiding principles (Hilborn et al. 2005, Costello et al. 2012, Costello et al. 2016, Melnychuk et al. 2017) and investigate how management and governance influence biodiversity and fish stock abundance, and to identify the management tools that can most effectively be used to sustain fisheries.

The study used recognised definitions of key categories of fisheries, as noted in Chapter 2:

- A *sustainable* fishery is where fishing pressure is at or less than the fishing mortality target (F-targ) and the stock size is around its target reference point level, i.e. long-term depletion due to overfishing has either not occurred or the stock has fully recovered from past excessive exploitation.
- A fishery was categorised as *depleted* when the stock had dropped below the target reference point (F-targ) for the fishery, which is typically set or assumed to be maximum sustainable yield (MSY). It is appreciated that stocks may dip into this zone via environmental variation, but in the main species considered here were in this state due to prolonged overfishing (excessive fishing pressure leading to depletion of the stock) and so the term is appropriate as a shorthand reference.
- A fishery was categorised as *collapsed* when the stock(s) had been fished until the biomass was depleted to <20% of unfished biomass levels, which is taken as the proxy limit reference point for stocks in Australia; beyond this point no targeted fishing pressure should be applied.

Overarching research focus

The overarching focus was whether there were key factors that alone or in combination, facilitate either fishery sustainability or increased risk of collapse. A key question, given the enormous effort invested in fisheries management, is why is it that so many fisheries around the world are considered to be overexploited or collapsed? Considerable effort has been given to tools and approaches that will predict the level of abundance at which a fish stock is threatened by collapse or extinction (Myers et al. 1995, Cook et al. 1997, Carlton et al. 1999, Halpern 2008, Hutchings et al. 2010). Most published studies that assess the global status of fisheries do not consider all aspects – ecological, legal, regulation, economic, and social – together, and few have attempted to identify specific sets of characteristics that distinguish sustainable fisheries from those that have collapsed (Haward and Vince 2008, Christie et al. 2017, Markus et al. 2017). In particular, there has been limited work on the key criteria that may indicate an *a priori* warning that particular fisheries are on a path to collapse.

Approach, methods, scope and limitations

A mixed multi-methods approach was used, integrating qualitative and qualitative research approaches and tools. Using expert knowledge and experience to identify and understand the main challenges in managing fisheries and ecosystems helped to identify the main tools that can be deployed to address these challenges. It is recognised that the 21 fisheries that form the core of this research represent a very small proportion of the world's fisheries. The fisheries analysed were, in addition, commercial high-value fisheries. This was to maximise data availability. Information on these fisheries was considered by senior fisheries scientists as the most reliable and was available via peer-reviewed scientific journals, management and governance reports, as well as peer-reviewed stock assessments. This is in stark contrast to the information available for the great majority of fisheries, which may be described as artisanal, subsistence, exploratory fisheries, or low value fisheries, or fisheries in countries with limited resources to collect and supply data. A second and recognised limitation is that the research did not include fisheries or experts from China and India, which are two major fishing nations. Significant attempts were made to incorporate insights from China and India, but were unfruitful. Other issues posed some limitations. Over time the status of a fishery can change. One of the fisheries studied, the Baltic cod fishery, was defined as sustainable early in the research project, based on its MSC certification and believed to have a viable stock/age distribution. The MSC certification for this fishery was later withdrawn.

Achieving sustainable fisheries: What determines stable or depleted fish stocks or fishery collapse?

The meta-analysis of 21 fisheries aimed at assessing potential contributing factors that could potentially help explain three main fishery management outcomes: a stable fishery, a depleted fishery or a collapsed fishery. As depleted and collapsed fisheries may not easily recover – causing high biological, economic and social costs – it is imperative we understand the risk factors so that they can be minimised.

The three categories of fisheries (sustainable, depleted and collapsed) were all found to have scores for individual criteria that ranged from low to high, with no fishery demonstrating uniformly high or low scores across all variables. For example, the sustainable Peruvian anchoveta fishery had the highest score for 'biology' (5), but a low score for 'environment' (2.2), and a very low score for 'governance' (0.5) (Nilsson et al. 2019a). The collapsed orange roughy stocks in Australia had the lowest 'biology' score (2.5), but a high 'management' score (4.5). For the total score (a maximum possible of 30), the sustainable Australian Northern prawn and Western Australian rock lobster fisheries scored the highest (25.1 and 24.7) overall, while the collapsed EU eel fishery and the depleted Patagonian toothfish in South Africa scored the lowest (15.1 and 15.2). The variables that scored the highest for all the 14 sustainable fisheries were biology, management, and industry criteria.

The biological criteria associated with sustainable fisheries included little or no disease present, and a size/age distribution amenable to sustaining a future stock (Table 1). Management criteria associated with sustainable fisheries mainly included MPAs or seasonal closures, setting a total allowable catch (TAC), and size and gear restrictions and had been certified. Industry criteria to promote sustainability were a high commercial value (which prompts efforts in management to sustain the economic value for the future), as well as the presence of a paid quota system (Table 1).

What did the research show?

Table 1: Key strengths and challenges in maintaining fisheries sustainability

Assessment of 21 fisheries: Factors contributing to *fishery sustainability*	Views from 188 marine experts: Factors contributing to *instability* and *poor sustainability*	Southern Ocean Fisheries Management, CCAMLR: Factors contributing to *ecosystem sustainability*
Strong science & understanding of stock structure, with typically good biological knowledge of the stocks	Overfishing	Commitment to science-based decision-making
Management ensure maintaining viable size/age distribution	Climate change	Strong and robust collaborative science
Low to medium risk of IUU fishing	Habitat destruction	Measures & processes to reduce IUU fishing
Governance structure and management perceived as open and transparent	Pollution from land	Consensus-based decision-making
Focus on environmental impacts of fishing	Ecosystem shifts	Pioneering focus on ecosystem-based management
Industry engagement and industry incentives (in particular certificates)	Ocean acidification	Industry engaged in management & participate as observers in scientific & management meetings
Monitoring programs in place	IUU fishing	Robust monitoring programs
Ecosystem-based fisheries management approach	Coastal development	Measures combatting by-catch
Species biology well known	Introduced species	Science and decision making processes are closely linked
	Lack of political will	Recognition of potential range shifts of temperate species poleward

All fisheries analysed face changes in their environment, as well as influences from businesses, societies and cultures. Previous literature has put much weight on the advantages in terms of resources available for fisheries management in developed economies (Halpern 2008, WorldBank 2008, Worm et al. 2009, ICES 2012), inferring that developing economies face greater struggles to deliver fishery sustainability (Evans et al. 2011, Barange et al. 2014, Sampson et al. 2015). However, the present research has shown that sustainable, depleted and collapsed fisheries were all present in both developed and developing economies around the world (Nilsson et al. 2019a). There was no difference between developing and developed economies with regards to the presence of sustainable *versus* depleted/collapsed fisheries, suggesting that for long-term commercial fisheries there are criteria other than governance alone that influence the sustainability of fished stocks.

The three fisheries that received the lowest overall scores (South African Patagonian toothfish, EU eel, and Namibian sardines) were defined as collapsed or depleted. However, the absolute score is not a reliable indicator of fishery sustainability by itself, as a number of ostensibly 'sustainable' fisheries had a relatively low overall score. Considering those fisheries that appear sustainable despite having a low overall score (anchoveta and hake in Peru, hake in South Africa, and Atlantic seabob in Suriname), they all had low scores for the governance and socioeconomic variables, but were early breeders and had a high score for the management variable (Nilsson et al. 2019a). The depleted Patagonian toothfish in South Africa also scored particularly poorly in the socioeconomic and governance variables, and being a late maturing species with a very high commercial value, its future sustainability is uncertain (Nilsson et al. 2016, Nilsson et al. 2019a).

IUU fishing

Perhaps not surprisingly, all the sustainable fisheries had a viable size and age distribution, while the collapsed and depleted ones did not. Interestingly, the collapsed fisheries all had a medium-high risk of illegal, unreported, and unregulated (IUU) fishing, while all the sustainable fisheries had a low-medium risk on this criterion. This supports the view that (i) high valued species are prone to IUU fishing, (ii) but, with appropriate measures, the risk of IUU may be reduced, and that (iii) high presence or risk of IUU fishing and corruption is a clear marker of a fishery in trouble (as it does not have the will or capacity to enforce regulations) (Schmidt 2005, Le Gallic and Cox 2006, FAO 2013). The survey of fisheries experts defined IUU fishing as one of ten major threats to fisheries, with some concern that up to as much as 60% of the total catch worldwide could potentially be defined as IUU fishing (Nilsson et al. 2019b).

A high score for the anti-corruption criteria meant that the government structure and management are perceived as open and transparent, which may help combat IUU fishing and corruption. While a high score for this anti-corruption criterion is not a guarantee of no corruption, it does indicate that the existence of regulatory measures can make it more difficult to perform illegal or unethical actions (TransparencyInternational 2012, FAO 2013, Miller et al. 2016). In the case study of how CCAMLR has worked on successfully combatting IUU fishing over the years, it was clear that they have used a range of different measures (Nilsson et al. 2016).

The collapsed eel and southern bluefin tuna fisheries stand out from all others, with a low overall score, particularly for industry, governance and management. Both species are migratory, traversing several national jurisdictions as well as in the high seas. Also being high valued species with slow breeding they are particularly vulnerable to IUU fishing and overexploitation (Patterson et al. 2008, Van den Thillart et al. 2009).

The meta-analysis and the CCAMLR case study also reiterated the importance of controlling and minimising IUU fishing (Nilsson et al. 2016, Nilsson et al. 2019a). This presents a significant challenge to fisheries management, such as the setting of a sustainable TAC, as it involves estimating (even informally) the level of IUU fishing by both legal and illegal operators, and by commercial, artisanal and recreational fishers (Agnew et al. 2009, Moutopoulos et al. 2017). The expert survey confirmed that IUU fishing is perceived to be a major threat to sustaining fisheries both nationally and globally (Nilsson et al. 2018). However, the CCAMLR case study indicates that efforts to minimise IUU fishing does have benefits in protecting stock abundance that justify the effort made by CCAMLR across a range of measures for combating IUU fishing, including rigorous data reporting, catch documentation schemes, vessel monitoring systems (VMSs), reporting of IUU vessels, and publication of an international IUU vessel list (CCAMLR 2017).

Sustainable fisheries

The fishery analysis showed a clear separation of the three stock categories, particularly of collapsed/depleted versus sustainable fisheries. The key criteria that best discriminate between sustainable and unsustainable fisheries (at least in terms of realised stock status) were prevalence of disease, use of fishery closures, certification of the fishery, characteristics of age and size distribution, and commercial value. This means that the sustainable fisheries had certification (apart from one), a high commercial value that prompted efforts in management, little or no disease present, and enforced management tools in place (such as MPAs or seasonal closures, TAC, and size and gear restrictions). Increasing values of all these criteria aligned with the sustainable fisheries.

Eleven of the 14 sustainable fisheries achieved high scores for all six variables, whilst the collapsed and depleted ones had a wider variability of scores across all variables (Nilsson et al. 2019a). However, the sustainable fisheries scored quite differently on governance, social and economic criteria. It is, however, noteworthy that while the sustainable (yet at a level way below optimum economic yield) Tasmanian rock lobster fishery and the sustainable Barents Sea cod fishery both scored very highly (4.3) on social and economic criteria, so did the collapsed Canadian cod fishery (4.6). None of the collapsed fisheries had similar scoring amongst the six different variables (i.e. all had their own idiosyncrasies), with the result that in order to sustain fisheries all five variables need to be addressed by practising in an integrated and adaptive manner (Nilsson et al. 2019a). This result also reinforces the complex basis to managing marine resources.

Although some studies show substantial evidence of increased ecological and economic performance from implementing a rights-based system, such as ITQ systems (Melnychuk et al. 2016), this may rather be a result from constrained total allowable catch, as the TAC is the basis for setting ITQs (Costello et al. 2008). Moreover, an increasing number of researchers are questioning the realised efficacy of ITQ systems (Gibbs 2010, Stage et al. 2016). ITQ systems on their own are insufficient for sustaining fisheries, and need to be accompanied by other measures and policies, including a system of compliance ensuring regulations are being applied and adhered to (Winder 2018). This was confirmed in the fisheries expert survey where ITQs were reported as an important tool for combating overexploitation (Nilsson et al. 2019b).

The fishery analysis showed that priorities for sustaining fisheries include: i) identifying whether the stock has a viable size and age distribution, as without it stocks risk being overfished no matter what management tools are in place; and ii) the sustainable fisheries showed that the application of ITQ or a membership fee to gain access to the resource can both play an important part in delivering sustainability (providing that TAC levels are appropriate). It was noteworthy that both developed and developing economies had both sustainable and collapsed fisheries and that once a fishery has collapsed then imposing a fishing moratorium does not guarantee a fishery will recover (Nilsson et al. 2019a).

In advancing fisheries management those directly involved need to appreciate the core drivers for management (Costello et al. 2016, Melnychuk et al. 2017). When faced with the challenges of marine resource management, both managers and other stake holders need to identify the conditions that contribute to sustainable fisheries (Anh et al. 2014). Is the Australian northern prawn fishery sustainable because biological traits are very well known? Or because management works closely with researchers and industry? Or because there is an ITQ system in place, controlling over-capacity? In all likelihood it is a mix of all these - no single variable or criterion marks a fishery as likely to be sustainable versus prone to collapse, rather it is the combination of a set of factors involving biological and environmental knowledge, governance and management impacts, socioeconomic and industry parameters.

Overall, the survey provided the opportunity to identify perceptions of key threats to sustainability of fisheries and fishery management needs. Responses to the survey indicated that the experts seemed largely aware of the key factors required to ensure sustainability. The survey outcomes also emphasized that the foundation of fisheries management is ensuring a long term sustainable stock abundance (Nilsson et al. 2019b). This is in line with the third analysis performed on sustaining fisheries, the case study of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) (Nilsson et al. 2016). CCAMLR’s working group on Fisheries Stock Assessment, which meets annually for two weeks to discuss and negotiate a science based TAC in an ecosystem-based approach (CCAMLR 2017), confirms healthy stocks as the foundation of sustainable exploitation in the long term.

The fishery analysis and the CCAMLR case study also reiterated the importance of controlling and minimising IUU fishing (Nilsson et al. 2016, Nilsson et al. 2019a). This presents a significant challenge to fisheries management, such as the setting of a sustainable TAC, as it involves estimating (even informally) the level of IUU fishing, both by legal and illegal operators, and by commercial, artisanal and recreational fishers (Agnew et al. 2009, FAO 2013, FAO 2016, Moutopoulos et al. 2017). The expert survey confirmed IUU fishing to be a major threat to sustaining fisheries both nationally and globally (Nilsson et al. 2018). However, the CCAMLR case study indicates that efforts to minimise IUU fishing does have stock abundance benefits that justify the effort CCAMLR puts into combating IUU fishing (CCAMLR 2017).

The fishery analysis also showed that although a fishery might have a high score for management and governance, without a medium or high score for biological knowledge sustainability is difficult to achieve. A majority of experts surveyed said that available science is not used to its fullest, suggesting science might not be fully integrated in the management process for the overexploited fisheries, or that decision makers have other priorities. Developing economies, such as South Africa and Peru, which are reported to be at higher risk for corruption, showed that sustainable fisheries are still possible to achieve in these conditions if scientific and management commitment is real. However, the number of depleted/collapsed fisheries in developed economies indicates that even with commitment of scientific and management resources, there is no guarantee that a fishery will be sustainable if significant levels of environmental stress exist, such as the cod fisheries in Newfoundland and the Baltic Sea (Nilsson et al. 2019a).

Matching environmental challenges with political commitment

The analysis of the expert survey showed the measures believed to help combat overexploitation include closures (area and seasonal), TAC, size limits, ecosystem-based fisheries management, gear restrictions, ITQs, ensuring compliance, monitoring and control (Nilsson et al. 2019b). This research also showed a clear need for a higher political will and commitment to combat the challenge of overexploitation, both nationally and globally (Nilsson et al. 2019b). An area identified as in particular need was research and long-term monitoring, where it was stated that more was needed to assist managers in prioritizing resources (Nilsson et al. 2019b). It was clear from the analysis that to retract from depletion and fisheries collapse and move to long term sustainable fisheries, both nationally and globally, scientific input must be matched with the same level of political commitment, including science-based conservation measures with relevant controls in place (Nilsson et al. 2019b).

CCAMLR and Southern Ocean fisheries

The case study of CCAMLR aimed to investigate whether long-term application of governance and management have, or have not, made a change to conservation and the sustainability of fisheries and ecosystems in the Southern Ocean. CCAMLR was established by international convention in 1982, today representing 25 nations, and pioneered an ecosystem approach to marine resource management within the CCAMLR Convention (CCAMLR 1982). The Convention includes a focus on a precautionary approach and has an explicit focus on rebuilding exploited stocks using the ecosystem approach (CCAMLR 1980). Since 1989 a wide range of conservation measures have been agreed upon by the commission, through a consensus-based process, binding to all its members to reach its target of rebuilding stocks using the ecosystem approach (CCAMLR 2017). In meeting all these combined commitments CCAMLR is seen as a leader and successful model among regional fisheries organisations (Willock and Lack 2006). The analysis of CCAMLR (chapter 4) found that four main factors stand out as contributing to positive outcomes for sustainability of fisheries and the ecosystems that support them: 1) a focus on science and science-based decision-making using monitoring of indicator species; 2) addressing IUU fishing; 3) addressing incidental catch – particularly of seabirds in close collaboration with the fishing industry; and 4) geopolitical factors (Nilsson et al. 2016). For those sustainable fisheries in the meta-analysis a close relationship was seen between science, conservation measures and management (Nilsson et al. 2019a). The science, underpinning all of CCAMLR's work, is organised around its scientific committee and its five working groups and several programs and schemes. Consensus in this politically sensitive geographical area could be argued to now define the lowest common denominator rather than, as seen in the early days, working towards the highest achievement (Nilsson et al. 2016). However, when the commission in 2016 adopted the measure to establish the world's largest MPA (1.55 million km^2) it proved that the consensus-based management model can still deliver positive and productive outcomes for conservation (CCAMLR 2016).

There are more than 10,000 marine species in the Southern Ocean, and managing its ecosystems involves considering, apart from fishing impacts, a large number of variables that may be changing at a fast rate due to climate change and ocean acidification (Meyer 2012, Kawaguchi et al. 2013, Watters George et al. 2017, Yang et al. 2018). A consensus-based management approach has many positive attributes, but given the potential delays and inertia in this kind of international decision-making it is also a risky way to govern large, highly complex ecosystems in the face of climate change which is shown to already be impacting the Southern Ocean (Flores et al. 2012, Kawaguchi et al. 2013, Nilsson et al. 2016). The expert survey showed that the need for ecosystem-based management with political commitment to support its adaptive and science-based approach is crucial to sustain fisheries and ecosystems (Nilsson et al. 2019b). Accepting this point, the question arises whether the lengthy time taken with consensus-based management through CCAMLR, together with a very low score for governance, can deliver suitable conservation measures in a timely manner given that climate change and its impacts are already affecting Southern Ocean ecosystems (Hanchet et al. 2015, Sales et al. 2017).

Science and governance – the need for integration

Fisheries management – at least of economically important species – in the majority of developed economies is largely science or evidence-based, even if science-based advice is not always followed in the political process (Naver 2013, Gascuel et al. 2016, Leite and Pita 2016, Ballesteros et al. 2017). The fisheries experts survey showed that the main constraints for effectively and efficiently implementing ecosystem-based fisheries management were:

1) lack of compliance;

2) not using scientific knowledge to its fullest potential;

3) IUU fishing; and

4) lack of political will.

The management of marine systems in general, and fisheries in particular, is highly complex and often characterised by paucity of information (Levin and Möllmann 2015, Ballesteros et al. 2017). It is very difficult to estimate even the abundance of target species, as well as to precisely determine what has been extracted from the ocean, let alone the effects on dependent species or species not directly impacted by fishing (Plagányi and Butterworth 2004, FAO 2013, FAO 2016). The expert survey indicated that science is not being used to its fullest and provided some potential reasons as to why this is so. It is possible that by keeping fisheries scientists apart from the management agency (as is the case in some countries), the research organisations are being used more in a consultancy role and are thereby not fully integrated into the whole management process. On the other hand, having a government agency performing both science and management may introduce its own challenges should the science process become hijacked by political agendas. Whatever the case, all three analyses showed that integration of governance and science is vital for sustaining fisheries and ecosystems. The expert survey highlighted the great challenge with successfully implementing the ecosystem approach, as the lack of data makes any management tools vulnerable to failure as managers are faced with trying to manage the unknown. Despite all the research and management efforts taking place in the world, a number of analyses emphasise the need for better integration of governance and science when managing fisheries (Walters 2007, Levin et al. 2009, Pullin et al. 2009, Fulton et al. 2014, Bundy et al. 2017). The strong and integrated presence of science in CCAMLR, with its many scientific working groups, ecosystem and precautionary approaches, and science-based decision making is likely to be the main reason to why CCAMLR has managed to avoid fisheries collapses (and indeed has seen some stocks rebuild from historically poor condition) since its beginning in the 1980s (Constable 2011, Brooks 2013, Hanchet et al. 2015).

Two contrasting examples suggest the benefit of an integrated approach. Scientists from the International Council for the Exploration of the Sea (ICES) advise the Oslo Paris Commission (OSPAR), the Baltic Marine Environment Protection Commission - Helsinki Commission (HELCOM), the North East Atlantic Fisheries Commission (NEAFC), the North Atlantic Salmon Conservation Organization (NASCO), and the European

Commission (EC) (ICES 2018), yet the decisions are still largely political with large amounts of overfishing within the European Union (Elmgren et al. 2015, Leite and Pita 2016, Voss et al. 2016, Ballesteros et al. 2017). The second example, the Commission for the Conservation for Antarctic Marine Living Resources (CCAMLR) has its scientific committee (and its many working groups) fully integrated within the organisation advising the Commission at the annual meetings. Many participants are part of the working groups, the scientific commission as well as the commission (CCAMLR 2015, CCAMLR 2017, CCAMLR 2017, CCAMLR 2017); and since the founding of CCAMLR in 1982 there have been recoveries of previous overfished stocks, and sustainable management of the Southern Ocean ecosystems, including fisheries (Constable et al. 2000, Hanchet et al. 2015). Another example of the integration of science and management is seen in Australia, where, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) provides significant scientific advice to the Australian Fisheries Management Authorities, other federal regulatory agencies and has a growing relationship with state fisheries management bodies. In this role CSIRO science has helped inform significant reforms and recoveries in Australia's federal fish stocks (Fulton et al. 2014). The success of this relationship has been because of the independent position of CSIRO – which has the role of the 'honest broker' providing frank but objective scientific advice to all parties – industry, regulatory agencies and conservation and community interest groups alike.

CCAMLR's work on sustaining fisheries for 37 years highlights that fisheries management successes are possible using the ecosystem approach despite the range of challenges that come with managing a system as extensive as the Southern Ocean. These challenges included monitoring, implementing and controlling science-based management measures, and these challenges were seen also for the 21 fisheries, and were confirmed by the 188 fisheries experts (Nilsson et al. 2019a, Nilsson et al. 2019b), suggesting a high global scientific awareness of challenges and tools to interpret science into management and governance.

Managing uncertainty in the context of climate change and ocean acidification

The meta-analysis showed that all but one of the 21 fisheries analysed (despite being sustainable, depleted or collapsed) had very high scores for the management variable, suggesting that management itself is not sufficient to ensure sustainability. It is also important to keep in mind that the presence of some kind of management per se does not automatically mean that the management protocols invoked are best practise or based on the best science available. It is necessary to acknowledge that some management is poor management … and there are many and diverse reasons why management practice is sometimes poor.

More and more studies are showing the effects on ecosystems caused by anthropogenic climate change and ocean acidification (Fossheim et al. 2015, Scheffers et al. 2016, FAO 2018). It is possible that management tools, such as MPAs, may increase the resilience to decrease some stressors, such as climate change (PAME 2017, Roberts et al. 2017), but for how much stress, and for how long? Long-term human-induced emissions of greenhouse gases causing warming climate is a global problem and a major challenge which impacts on local fish abundance world-wide (FAO 2018). What can local, regional and even national fisheries management do about that?

Fully practising ecosystem-based management demands healthy marine ecosystems in order to also achieve the other goals of a sustainable economy and equitable society (Fulton et al. 2014, Fernandino et al. 2018). This, in turn, asks for an adaptive management process with no or few boundaries between science and politics, bridged by natural resource managers. This, in itself, can be a major challenge as politician have other interests to balance as well, such as employment, economics, international relations, national security and more (Reed et al. 2009). As we now see unprecedented changes to marine ecosystems caused by climate change and ocean acidification, which are clearly factors outside the control of fisheries managers, one may wonder how these challenges will reflect in policy and management of fisheries. Considering that CCAMLR started bringing ecosystem-based management into the international arena in the 1970s when discussions started about creating a convention for the Southern Ocean, and yet most fisheries still do not practise it (or at least not fully), one may wonder how the incorporation of climate induced factors will pan out in fisheries management to sustain abundance long term. It was seen with the Australian west coast rock lobster fishery how management quickly adjusted the TAC when it was discovered that warming water unexpectantly reduced the number of recruits (Caputi et al. 2013), but how many fisheries in the world have as rigorous data sets and adaptive management in place as does the Western Australia rock lobster fishery?

In developing economies with a higher risk of corruption, achieving sustainable fisheries is still possible providing that sound scientific and management processes and commitments are in place, as was shown for the South African and Namibian fisheries, although the opposite was also seen. There clearly is no guarantee that overexploitation will not occur in developed economies with plenty of scientific and management resources deployed, as was seen for some Australian, European and Canadian fisheries.

The expert study indicated that the common position of the respondents is that the use of a mixture of top-down and bottom-up organisation and institutional forms is important for success, as is the importance of stakeholder participation. It is also worth noting that human cognition is not infallible. When experts were asked directly about illegal, unreported and unregulated fishing, 99% of the respondents saw it as a global issue. However, when put against other challenges, close to 70% of the policy-makers and scientists believed that IUU fishing is not a major threat to national fisheries, despite the fact that almost 80% of the fishers themselves identified IUU as a major threat. This suggests that there is a gap in the discourse and management of IUU fishing that needs closer consideration.

The sustainable fisheries all had high scores on biology, management, and industry criteria. None of the collapsed fisheries had a similar pattern of scoring across the six variables, supporting the notion that different fisheries can collapse for different reasons, that managing marine resources is complex, and that an adaptive approach with explicit attention to all of the variables that were identified here is essential to maximise the likelihood of achieving sustainable practice in commercial fisheries. The survey conducted by marine experts from 34 nations reinforced the magnitude of the challenges in sustaining fisheries. It identified key issues underpinning the use of an ecosystem management approach, such as complexity, the high degree of connectivity, difficulties associated with observing ocean processes and monitoring flora and fauna. The fact that 99% of the respondents believed that IUU fishing still is a global problem and 65% estimated the global level of IUU fishing to be between 31 and 60% of the total catch worldwide is, naturally, a major concern.

It was clear from the research that to move from fisheries depletion and fisheries collapse then scientific input must be matched with a high level of political commitment, and that research and long-term monitoring are key to assist managers in their prioritization of actions and resources. CCAMLR is an example how science underpins the ecosystem-based management approach taken for managing fisheries in the Southern Ocean. The expert analysis showed that there is a strong perception that scientific knowledge is not being used to its fullest potential and that in turn is the main constraint for effectively and efficiently implementing ecosystem-based fisheries management.

This research highlighted that priorities for sustaining fisheries include:

- Identifying whether the stock has a viable size and age distribution, as without it stocks risk being overfished no matter what management tools are in place. For ecosystem-based management to work there needs to be sound monitoring and assessments processes in place;
- An ITQ system played an important part in sustaining fisheries. It does, of course, require that a sustainable TAC is set in the first place, and that requires rigorous analysis and adequate data;
- Developed and developing economies both had sustainable and collapsed fisheries, suggesting that with sound science and appropriate management tools in place sustaining fisheries is possible despite a high risk for corruption; and
- Even when a moratorium on fishing is in place, a collapsed fishery may take a long time to recover, as seen with the Canadian cod fishery and the Australian orange roughy fishery.

It was clear from all the three analysis that to move away from fishery depletion and fisheries collapse as an end point, then scientific input must be matched with a high level of political commitment, and that research and long-term monitoring are key to assist managers in their prioritization of actions.

Findings, conclusions and direction for further work

This thesis has provided some insights on how to sustain fisheries. A key finding is that sustainable fisheries are associated with sound biological knowledge, having a large range of management tools in place, and industry controls (such as a paid quota system). It is clear that sustainable fisheries are supported by focused scientific input and management tools and measures (MPAs, ITQs, gear restrictions and stakeholder participation), but also that political will (governance) to ensure sustainability is a critical element.

There are some consistent results across the three components of the thesis. The survey of 188 fisheries experts confirmed the findings in both the meta-analysis and the CCAMLR case study, and went further to highlight the range of management tools that have proven efficient to sustain fisheries worldwide (if implemented and applied properly and conscientiously) (Nilsson et al. 2019b). Since its beginning in 1982, CCAMLR has managed to avoid collapse of the fisheries under its remit, has overseen substantial stock recovery in areas where degradation had occurred in the past and has seen through a number of continuously up-dated conservation measures with the aim of providing for marine conservation and fisheries sustainability (Nilsson et al. 2016). The activities performed by CCAMLR match the measures in place for the 14 sustainable fisheries and align well with the experts' view on how to sustain fisheries (Nilsson et al. 2019a). A common thread through the three analyses is the importance of scientific knowledge and establishment of management programs, including monitoring and controls, but also that political will and long-term stability of management are necessary to ensure sustainable marine ecosystems long term (Nilsson et al. 2016, Nilsson et al. 2019a, Nilsson et al. 2019b).

To move from fisheries depletion and fisheries collapse, scientific input must be matched with a high level of political commitment, where research and long-term monitoring are key to assist managers in their prioritization of actions and resources. CCAMLR is an example how science underpins the ecosystem-based management approach taken for managing fisheries in the Southern Ocean. The expert analysis showed that there is a strong perception that scientific knowledge is not being used to its fullest potential and that this is the main constraint for effectively and efficiently implementing ecosystem-based fisheries management.

Considering ecosystem-based management was promoted in the international arena as early as the 1970s and is still to be fully adopted and integrated for most fisheries and parts of the world, one wonders how we will be able to manage marine ecosystems in the face of climate change and ocean acidification, which demands yet a higher level of adaptive management than adjusting a TAC.

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Appendix 1: Criteria scoring

Criteria	Score 2	Score 1	Score 0
		Variable 1 - Biology	
Breeding	fast growing/early breeders	slow growing/late breeders	-
Migratory	no/little migration	migratory	-
Fecundity	high recruitment	low recruitment	-
Diet specialisation	no special diet	special diet	-
Age / size distribution	viable age/size distribution for sustainable stock	no viable age/size distribution for sustainable stock	-
Habitat specialisation of life stages	particular habitat specialisation during some life stages	no habitat specialisation	-
Spatial connectivity	larvae dispersal	no/low larvae dispersal	-
		Variable 2 - Environment	
Ocean Health Index	healthy (90 and above)	medium health (80-89)	low health (<80)
Clean Waters (OHI)	low contaminated (>90)	medium contaminated (80-89)	high contamination (<80)
Carbon storage	>80	60-80	<60
Anthropogenic influence to habitat (fishing, pollution)	low/absent	high	very high
Disease/virus/toxic algae blooms/invading spp	little	high	very high
Acidification	no effect (fish)	effect (calcification, crustaceans, mainly)	-
Hot spot area (climate change)	no hotspot area	hotspot area	-
Climate variability	no regular impact	some impact	regular impact

Variable 3 - Social and economic			
Human Development Index (HDI)	developed nations (green, 0.75-0.9)	developing nations (light green, yellow, orange, 0.74-0.5)	underdeveloped nations (red, <0.4)
Coastal Livelihoods & Economies (from OHI)	increased economics	no economic development	decreased economic development, or no info
Poverty and Economic Decline Index	low decline (<1.6)	medium decline (1.7-5.5)	high decline (>5.5)
Education Index	>.9	<.9	<.8
Community involvement	high	low	none
Artisanal fishing (OHI)	high access	low access to fishing	very low access to fishing
Vital protein source	low	medium	high
Variable 4 - Industry			
Subsidies (case by case evaluation)	positive for regulated countries	-	negative for unregulated fisheries,
Commercial value	low risk of IUU fishing	medium risk of IUU fishing	high risk of IUU fishing
Paid quota or membership fee	yes, low fee	-	no / no info found
Variable 5 - Governance			
Global Peace Index (GPI)	high peace (light yellow)	medium peace (yellow/orange)	low peace (red/yellow/brown)
Gini Index	high equality	medium inequality	high inequality
Fragile State Index	sustainable	stable	alert/warning
Anti-corruption Perceptions Index (where more than one country was involved in management, the average score was used)	low corruption (yellow)	medium corruption (orange)	high corruption (red)
State Legitimacy	good (<1.7)	weak (1.8-4.9)	poor (>5)

Variable 6 - Management			
Fisheries legal framework	yes	some	no
Management agency	yes	-	no
Overall food provision	sustainable (>80)	overexploited/rebuilding (21-79)	high risk of collapsing (<20) or no info
Life history known	high knowledge	low knowledge	no knowledge
Stakeholder involvement	yes	little	no
Stock quota	yes	-	no
Property rights	yes	partly	no
Catch/gear restrictions	yes	-	no
Seasonal closures	yes	planned	no
Spatial management	yes	in the process	no/no info
Monitoring Compliance System (MCS)	yes	some, in the process	no plan/program/info
Certification	MSC/MBA cert	other certification	no certification
Science-based decision making	yes	mentions it/somewhat	no
Food web knowledge	yes	some	no
Breeding/size protection	protection (area or spp)	some protection	no protection
Capacity building	yes	little	no info
By-catch/mortality management (including IUU fishing)	management in place/part of quota	some	no
Stock assessments	population dynamics model	catch rate vs historical model	none
Stock survey	scientifically collected	catch base	no survey
EBFM	yes	-	no
VMS	yes	some	no

Appendix 2: Meta-analysis 21 fisheries - raw data

Fifty-one criteria were given a score of 0-2.

Meta-analysis	Biology							Environment								Social and Economic							Industry			Governance				
CRITERIA	Breeding	Migratory	Fecundity	Diet specialisation	Age / size distribution	Habitat specialisation of life stages	Spatial connectivity	Ocean Health Index	Clean Waters (OHI)	Carbon storage	Anthropogenic influence to habitat	Disease / virus / toxic algae blooms / invading spp	Acidification	Hot spot area	Climate variability	HDI	Coastal Livelihoods & Economies	Poverty and Economic Decline Index	Education Index (100=best)	Community involvement	Artisanal fishing (OHI)	Vital protein source	Subsidies	Commercial value	Paid quota	GPI (Global Peace Index)	Gini Index	Fragile State Index	Corruption Perceptions Index	State Legitimacy
FISHERY																														
Alaska pollock, USA	1	2	2	2	2	1	2	0	1	1	1	2	2	1	2	2	1	1	1	2	2	1	2	1	2	1	0	2	2	1
Anchoveta, Peru	2	2	2	2	2	2	2	0	0	0	1	2	2	2	0	1	1	1	0	1	1	1	1	2	2	1	0	0	0	0
Atlantic seabob, Suriname	2	2	2	1	2	1	0	0	0	2	1	2	1	2	2	1	2	0	0	1	1	1	1	1	2	0	0	1	0	0
Cod, Canada	1	1	2	2	1	1	2	0	2	0	1	1	2	1	2	2	2	2	1	2	2	2	1	1	2	2	1	2	2	2
Cod, Iceland	1	1	2	2	2	1	2	0	2	0	1	1	2	1	2	2	1	1	1	2	1	2	2	1	2	2	0	2	2	2
Cod, Norway/Russia	1	1	2	2	2	1	2	0	2	0	1	1	2	1	2	2	2	1	1	2	2	2	2	1	2	1	1	1	0	1
Cod, EU	1	1	2	2	2	1	2	0	2	1	0	2	2	2	1	2	2	1	1	1	1	2	1	1	0	2	2	2	1	2
Eel, high seas/EU	1	1	1	2	0	1	2	0	1	1	0	1	2	2	2	2	1	0	1	2	1	0	1	1	0	2	2	1	0	0
Hake, Peru	2	1	2	1	2	1	2	0	0	0	1	2	2	2	1	1	1	1	1	1	1	1	1	2	2	1	0	0	0	0
Hake, South Africa	1	1	1	2	2	1	1	0	1	2	1	2	2	1	1	0	2	0	0	0	1	2	2	2	2	1	0	1	0	0
Herring, Iceland	1	1	2	2	2	1	2	0	2	1	1	2	2	1	2	2	1	1	2	2	1	1	2	2	2	2	0	2	2	2
Northern Prawn Fishery, Asutralia	2	2	2	2	2	1	2	0	2	2	1	2	1	2	1	2	2	1	2	1	2	1	1	2	2	2	0	2	2	2
Orange roughy, Australia	1	1	2	2	0	1	0	0	2	2	1	1	2	1	2	2	2	1	2	0	2	1	1	1	2	2	0	2	2	2
Rock lobster, Australia (TAS)	2	2	2	2	2	1	2	0	2	2	1	1	1	1	1	2	2	1	2	1	2	2	1	2	2	2	0	2	2	2
Rock lobster, Austarlia (WA)	2	1	2	2	2	2	2	0	2	2	1	2	1	1	1	2	2	1	2	1	2	0	2	2	2	2	0	2	2	2
Sardine, Namibia	2	1	2	1	0	1	2	0	2	0	1	1	2	1	0	0	1	0	0	1	2	1	2	0	2	2	0	0	0	1
Southern bluefin tuna, CC	1	1	2	2	1	1	2	0	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	0	2	1	0	2	0	1
Patagonian toothfish, Australia	1	2	2	2	2	2	2	1	2	1	1	2	2	1	1	2	0	1	2	1	2	0	1	2	2	2	0	2	2	2
Antarctic toothfish, CCAMLR	1	1	2	2	2	1	2	0	2	2	1	2	2	1	1	1	2	1	0	0	0	0	1	1	2	0	0	0	0	0
Patagonian toothfish, South Africa	1	1	2	2	1	2	1	2	2	0	1	2	2	1	2	0	0	0	0	0	0	0	2	0	2	0	0	1	0	0
Patagonian toothfish, UK	1	1	2	2	2	1	2	0	2	0	1	2	2	1	0	2	0	1	2	0	0	0	2	1	2	2	1	2	2	2

cont. Appendix 2

	Management																				
CRITERIA	Fisheries legal framework	Management agency	Overall food provision	Life history known	Stakeholder involvement	Stock quota	Property rights	Catch and gear restrictions	Seasonal closures	Spatial management	Monitoring Compliance System	Certification	Science-based decision making	Foodweb knowledge	Breeding/size protection	Capacity building	By-catch / mortality management	Stock assessments	Stock survey	EBFM	VMS
FISHERY																					
Alaska pollock, USA	2	2	1	2	2	2	0	2	2	2	2	2	2	2	1	2	2	2	2	2	2
Anchoveta, Peru	2	2	2	2	2	2	2	2	2	1	1	0	2	2	2	1	0	1	1	0	2
Atlantic seabob, Suriname	2	2	2	1	2	2	2	1	0	2	2	2	2	1	2	2	2	2	2	0	2
Cod, Canada	2	2	1	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2
Cod, Iceland	2	2	1	2	1	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2
Cod, Norway/Russia	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Cod, EU	2	2	1	2	2	2	1	2	2	1	2	2	2	2	2	1	2	2	2	0	2
Eel, high seas/EU	2	2	0	2	2	0	0	2	0	0	1	0	2	2	1	1	0	2	2	0	0
Hake, Peru	2	2	2	2	1	2	2	2	2	2	1	0	1	2	0	1	2	2	2	0	2
Hake, South Africa	2	2	1	2	1	2	2	2	0	2	2	2	2	2	2	1	1	2	2	0	2
Herring, Iceland	2	2	1	2	2	2	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2
Northern Prawn Fishery, Asutralia	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Orange roughy, Australia	2	2	1	2	2	2	2	2	0	2	2	1	2	2	2	2	2	2	2	2	2
Rock lobster, Australia (TAS)	2	2	2	2	2	2	2	2	2	0	2	0	2	2	1	1	2	2	2	2	0
Rock lobster, Austarlia (WA)	2	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0
Sardine, Namibia	2	2	1	2	2	2	2	2	1	2	2	0	2	2	2	2	2	1	0	0	1
Southern bluefin tuna, CCSB	2	1	2	2	2	2	2	2	0	2	1	0	2	1	0	1	1	2	2	0	2
Patagonian toothfish, Australia	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	2
Antarctic toothfish, CCAMLR	2	2	2	1	2	2	0	2	2	2	2	1	2	1	0	1	2	2	2	2	2
Patagonian toothfish, South Africa	2	2	1	1	2	2	2	2	2	2	2	0	2	2	0	2	2	1	1	0	2
Patagonian toothfish, UK	2	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Appendix 3: Meta-analysis 21 fisheries - references

VARIABLES	Biology							Environment							
CRITERIA	Breeding	Migratory	Fecundity	Diet specialisation	Age / size distribution	Habitat specialisation of life stages	Spatial connectivity	Ocean Health Index	Clean Waters (OHI)	Carbon storage	Anthropogenic influence to habitat	Disease / virus / toxic algae blooms	Acidification	Hot spot area	Climate variability
FISHERIES															
Alaska pollock, USA	www.st. nmfs.no	ww.fao. org/fish	ww.fao. org/fish	ww.fao. org/fish	www.afs c.noaa.g	ww.fish watch.g	ww.afsc. noaa.go	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ww.fish watch.g	ww.iucn gisd.org	ww.afsc. noaa.go	oceans- of-	onlineli brary.wi
Anchoveta, Peru	ww.fish base.org	ww.fao. org/fish	ww.fao. org/fish	ww.iucn redlist.o	ww.worl dbank.o	onlineli brary.wi	al.archi ves-	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ww.natu re.org/o	ww.iucn gisd.org	www.nc bi.nlm.n	www.nc bi.nlm.n	www.nc bi.nlm.n
Atlantic seabob, Suriname	ww.fao. org/fish	ww.fao. org/fish	ww.msc. org/trac	ww.msc. org/trac	ww.msc. org/trac	ww.fao. org/fish	ww.msc. org/trac	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ure.ilvo. vlaande	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	ww.msc. org/trac
Cod, Canada	ww.fish base.org	ww.phys .ocean.d	ww.phys .ocean.d	sajourn als.onli	ww.phys .ocean.d	ww.fish base.org	sajourn als.onli	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ww.fosa f.co.za/i	ww.fosa f.co.za/i	onlineli brary.wi	oceans- of-	pdfs.se mantics
Cod, Iceland	www.fis hsource.	www.fis hsource.	www.fis hsource.	www.fis hsource.	academi c.oup.co	ww.fish base.org	urnals.p los.org/	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	www.sci encedire	ww.fish base.org	onlineli brary.wi	oceans- of-	www.sci encedire
Cod, Norway/Russia	ww.fish eries.no	ww.fish eries.no	ww.msc. org/trac	ww.fish eries.no	ww.msc. org/trac	shbase. org/sum	ww.mon tereybay	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	aslopub s.online
Cod, EU	3.amazo naws.co	academi c.oup.co	www.sci encedire	academi c.oup.co	ww.ices. dk/sites	academi c.oup.co	ww.save ourbalti	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	urnal.na fo.int/d	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	urnal.na fo.int/d
Eel, high seas/EU	ww.fish base.org	ww.iucn redlist.o	shbase. org/Sum	ww.fish base.org	ww.iucn redlist.o	ww.iucn redlist.o	ww.fish base.org	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.fao. org/fish	onlineli brary.wi	oceans- of-	urnal.na fo.int/d
Hake, Peru	shbase. org/Sum	ooks.go ogle.co	ww.fish base.org	www.co m.univ-	ww.und ercurren	quaticc ommons	shbase. org/Sum	ww.icm. csic.es/r	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	ww.icm. csic.es/r
Hake, South Africa	ww.fish base.se/	www.ta ndfonlin	www.ta ndfonlin	ww.fish base.se/	ww.fish base.se/	www.ta ndfonlin	www.ta ndfonlin	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ww.fosa f.co.za/i	ww.fosa f.co.za/i	ww.fosa f.co.za/i	ww.fao. org/doc	ww.fao. org/doc
Herring, Iceland	ww.fish base.org	ience.sc iencema	ience.sc iencema	ww.fish base.org	ww.fish base.org	ience.sc iencema	ww.fish base.org	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	www.sci encedire
Northern Prawn Fishery, Asutralia	ww.afm a.gov.au	ww.afm a.gov.au	ww.afm a.gov.au	ww.afm a.gov.au	ww.afm a.gov.au	ww.afm a.gov.au	ww.publ ish.csir	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	dl.brs.g ov.au/d
Orange roughy, Australia	ww.afm a.gov.au	ww.fish. govt.nz/	onlineli brary.wi	ww.int- res.com	ww.cpor t.net/as	ww.afm a.gov.au	ww.plos one.org/	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	ueocean .org/doc
Rock lobster, Australia (TAS)	ww.clim atechan	ww.ima s.utas.e	ww.ima s.utas.e	ww.ima s.utas.e	ww.ima s.utas.e	www.sci encedire	www.sci encedire	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.dpi w.tas.go	onlineli brary.wi	oceans- of-	onlineli brary.wi
Rock lobster, Austarlia (WA)	ww.fish. wa.gov.	ww.fish. wa.gov.	ww.fish. wa.gov.	ww.fish. wa.gov.	ww.fish. wa.gov.	ww.fish. wa.gov.	ww.fish. wa.gov.	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	ww.fish. wa.gov.
Sardine, Namibia	ww.publ ish.csir	shbase. org/Cou	ww.mfm r.gov.na	shbase. org/sum	onlineli brary.wi	ww.publ ish.csir	nlinelib rary.wil	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	ww.fao. org/doc	oceans- of-	ww.fao. org/doc
Southern bluefin tuna, CCSBT	ww.ccsb t.org/sit	ww.ccsb t.org/sit	ww.ccsb t.org/sit	ww.envi ronment	ww.envi ronment	ww.ccsb t.org/sit	ww.ccsb t.org/sit	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.fish base.org	ww.ncbi .nlm.nih	oceans- of-	ww.fish. gov.au/r
Patagonian toothfish, Australia	ww.fish base.org	www.sci encedire	ww.afm a.gov.au	ww.jstor .org/sta	ww.afm a.gov.au	www.sci encedire	www.ca mbridge	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	ink.spri nger.co
Antarctic toothfish, CCAMLR	ww.fish base.org	dit.niwa .co.nz/si	dit.niwa .co.nz/si	dit.niwa .co.nz/si	t.niwa.c o.nz/site	dit.niwa .co.nz/si	ww.envi ronment	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.niw a.co.nz/	onlineli brary.wi	oceans- of-	ww.cebc .cnrs.fr/
Patagonian toothfish, South Africa	ww.fish base.org	ink.spri nger.co	ink.spri nger.co	w2.odu. edu/sci/	37.158. 44.66/m	37.158. 44.66/m	ink.spri nger.co	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ww.mon tereybay	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	ink.spri nger.co
Patagonian toothfish, UK	ww.fish base.org	ink.spri nger.co	www.sci encedire	www.sci encedire	www.go v.gs/doc	w2.odu. edu/sci/	ink.spri nger.co	ww.ocea nhealthi	ww.ocea nhealthi	ww.ocea nhealthi	ience.sc iencema	ww.iucn gisd.org	onlineli brary.wi	oceans- of-	onlineli brary.wi

VARIABLES	Social and Economic							Industry			Governance				
CRITERIA	HDI	Coastal Livelihoods & Economies	Poverty and Economic Decline	Education Index*	Community involvement	Artisanal fishing (OHI)	Vital protein source	Subsidies	Commercial value	Paid quota	GPI (Global Peace Index)	Gini Index	Fragile State Index	Corruption Perceptions Index	State Legitimacy
FISHERIES															
Alaska pollock, USA	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fish watch.g	www.np fmc.org/	ww.nrcr esearch	www.np fmc.org/	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Anchoveta, Peru	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	www.sci encedire	ac.els- cdn.com	www.sci encedire	publicat ions.iad	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Atlantic seabob, Suriname	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	z.be/imi sdocs/p	www.res earchga	z.be/imi sdocs/p	www.res earchga	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Cod, Canada	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.stat ssa.gov.	ww.cons ervation	ww.trad emap.or	ww.fao. org/doc	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Cod, Iceland	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ink.spri nger.co	holar.go ogle.se/	ww.stati ce.is/?P	ww.l- encre-	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Cod, Norway/Russia	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	chive.un u.edu/u	www.fis hsource.	ww.fish eries.no	ww.fish eries.no	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Cod, EU	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	www.sci encedire	c.europ a.eu/fis	ww.save ourbalti	c.europ a.eu/fis	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Eel, high seas/EU	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	ceana.o rg/sites/	.europa. eu/fishe	c.europ a.eu/fis	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Hake, Peru	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	s.com/fi s/world	ww.ocea nhealthi	ww.fish base.org	ac.els- cdn.com	ww.fish base.org	ac.els- cdn.com	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Hake, South Africa	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.trad emap.or	ww.cons ervation	ww.stat ssa.gov.	ww.sads tia.co.za	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Herring, Iceland	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	www.ice land.is/i	ww.fish eries.is/	www.oe cd.org/e	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Northern Prawn Fishery, Asutralia	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	academi c.oup.co	ww.afm a.gov.au	ww.afm a.gov.au	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Orange roughy, Australia	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	ww.fish. govt.nz/	academi c.oup.co	ww.fish. govt.nz/	ww.afm a.gov.au	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Rock lobster, Australia (TAS)	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	academi c.oup.co	ww.dpi w.tas.go	ww.afm a.gov.au	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Rock lobster, Austarlia (WA)	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	academi c.oup.co	ww.fish. wa.gov.	ww.afm a.gov.au	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Sardine, Namibia	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	ww.fund forpeac	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	www.cb d.int/do	ww.mfm r.gov.na	ww.mfm r.gov.na	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Southern bluefin tuna, CCSBT	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	academi c.oup.co	ww.ccsb t.org/sit	www.cc sbt.org/	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Patagonian toothfish, Australia	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	ww.afm a.gov.au	www.sci encedire	ww.afm a.gov.au	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Antarctic toothfish, CCAMLR	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	www.cc amlr.org	www.sci encedire	www.cc amlr.org	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Patagonian toothfish, South Africa	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	ww.fao. org/fish	www.sci encedire	www.go v.za/site	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac
Patagonian toothfish, UK	dr.undp. org/en/s	ww.ocea nhealthi	ndforpe ace.org/	http://w ww.fund	dr.undp. org/en/s	ww.ocea nhealthi	ww.fao. org/doc	ww.gov. gs/fishe	www.jo urnals.u	ww.gov. gs/fishe	ww.visi onofhu	ata.worl dbank.o	ww.fund forpeac	www.tra nsparen	ww.fund forpeac

*Education has since been removed as an indicator with Fund for Peace.

VARIABLES	Management									
CRITERIA	Fisheries legal framework	Management agency	Overall food provision	Life history known	Stakeholder involvement	Stock quota	Property rights	Catch and gear restrictions	Seasonal closures	Spatial management
FISHERIES										
Alaska pollock, USA	afisheries.no aa.gov/sites/	afisheries.no aa.gov/sites/	shwatch.gov/ seafood_prof	elibrary.wile y.com/doi/ab	shbase.org/s ummary/Ther	afsc.noaa.go v/REFM/Docs	researchgate. net/publicati	shwatch.gov/ seafood_prof	shwatch.gov/ seafood_prof	http://www.fi shwatch.gov/
Anchoveta, Peru	cations.iadb. org/bitstrea	roduce.gob.p e/index.php/	ceanhealthin dex.org/Goal	rest.ird.fr/per sonnel/ppenv	csic.es/bitstr eam/10261/2	cations.iadb. org/bitstrea	cations.iadb. org/bitstrea	ishsource.org /stock_page/	rcresearchpr ess.com/doi/	bcd.org/pdf/ presentation/
Atlantic seabob, Suriname	sc.org/track- a-	sc.org/track- a-	ceanhealthin dex.org/Goal	sciencedirect .com/science	sc.org/track- a-	sc.org/newsr oom/news/su	sc.org/newsr oom/news/su	sc.org/newsr oom/news/su	sc.org/track- a-	sc.org/track- a-
Cod, Canada	ac.dfo- mpo.gc.ca/aq	fo- mpo.gc.ca/fm	ceanhealthin dex.org/Goal	rcresearchpr ess.com/doi/	pringer.com/ chapter/10.1	rcan.gc.ca/17 200	atssa.gov.za/ publications/	atssa.gov.za/ publications/	shaq.gov.nl.c a/research_d	shaq.gov.nl.c a/research_d
Cod, Iceland	sheries.is/ma nagement/go	sheries.is/ma nagement/go	ceanhealthin dex.org/Goal	rs/jesnil/App Data/Local/P	mic.oup.com/ icesjms/artic	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis
Cod, Norway/Russia	ishsource.org /stock_page/	regjeringen.n o/globalasse	ceanhealthin dex.org/Goal	rs/jesnil/App Data/Local/P	sheries.no/ec osystems-	sheries.no/P ageFiles/423	sheries.no/ec osystems-	sheries.no/ec osystems-	sheries.no/ec osystems-	sc.org/track- a-
Cod, EU	opa.eu/fisher ies/cfp_en	opa.eu/fisher ies/cfp_en	ceanhealthin dex.org/Goal	rs/jesnil/App Data/Local/P	azonaws.com /academia.ed	- cdn.com/S03	opa.eu/fisher ies/sites/fish	opa.eu/fisher ies/sites/fish	opa.eu/fisher ies/sites/fish	opa.eu/fisher ies/sites/fish
Eel, high seas/EU	lex.europa.eu /LexUriServ/L	lex.europa.eu /LexUriServ/L	ceanhealthin dex.org/Goal	e.sciencemag .org/content/	shbase.org/R eproduction/	lex.europa.eu /LexUriServ/L	lex.europa.eu /LexUriServ/L	lex.europa.eu /LexUriServ/L	lex.europa.eu /legal-	opa.eu/fisher ies/cfp/contr
Hake, Peru	google.com.a u/books?id=S	ishsource.org /stock_page/	ceanhealthin dex.org/Goal	pringer.com/ chapter/10.1	shbase.org/s ummary/146	ishsource.org /stock_page/	ishsource.org /stock_page/	ishsource.org /stock_page/	cations.iadb. org/bitstrea	/fis/worldne ws/worldnew
Hake, South Africa	aff.gov.za/daf fweb3/Branc	http://www.d aff.gov.za/	ceanhealthin dex.org/Goal	da.agric.za/d oaDev/sideM	pringer.com/ chapter/10.1	adstia.co.za/f ishery/the-	adstia.co.za/f ishery/the-	atssa.gov.za/ publications/	da.agric.za/d oaDev/sideM	da.agric.za/d oaDev/sideM
Herring, Iceland	sheries.is/ma nagement/fis	skistofa.is/en glish	ceanhealthin dex.org/Goal	elibrary.wile y.com/doi/ful	elibrary.wile y.com/doi/ful	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis
Northern Prawn Fishery, Asutralia	fma.gov.au/m anaging-our-	fma.gov.au/m anaging-our-	ceanhealthin dex.org/Goal	mic.oup.com/ icesjms/artic	amer.unsw.e du.au/public	siro.au/en/O utcomes/Oce	fma.gov.au/m anaging-our-	fma.gov.au/fi sheries/north	fma.gov.au/m anaging-our-	fma.gov.au/m anaging-our-
Orange roughy, Australia	fma.gov.au/a bout/legislati	fma.gov.au/p ortfolio-	ceanhealthin dex.org/Goal	pringer.com/ article/10.10	sh.govt.nz/NR /rdonlyres/EF	fma.gov.au/o range-	sh.govt.nz/NR /rdonlyres/EF	port.net/asse ts/uploads/fi	sh.govt.nz/NR /rdonlyres/EF	.tas.gov.au/s ea-fishing-
Rock lobster, Australia (TAS)	fma.gov.au/a bout/legislati	.tas.gov.au/s ea-fishing-	ceanhealthin dex.org/Goal	sciencedirect .com/science	imatechange. gov.au/~/med	.tas.gov.au/s ea-fishing-	.tas.gov.au/s ea-fishing-	.tas.gov.au/s ea-fishing-	.tas.gov.au/s ea-fishing-	.tas.gov.au/s ea-fishing-
Rock lobster, Austarlia (WA)	fma.gov.au/a bout/legislati	sh.wa.gov.au /Species/Roc	ceanhealthin dex.org/Goal	sciencedirect .com/science	sh.wa.gov.au /Species/Roc	sh.wa.gov.au /Species/Roc	sh.wa.gov.au /Species/Roc	sh.wa.gov.au /Documents/	sh.wa.gov.au /Documents/	sh.wa.gov.au /Species/Roc
Sardine, Namibia	fmr.gov.na/d ocuments/12	fmr.gov.na/d ocuments/12	ceanhealthin dex.org/Goal	shbase.org/S ummary/Spec	fmr.gov.na/d ocuments/12	fmr.gov.na/d ocuments/12	fmr.gov.na/d ocuments/12	fmr.gov.na/fe es-and-	cbd.int/doc/n bsap/fisherie	ecd.org/tad/f isheries/Nam
Southern bluefin tuna, CCSBT	csbt.org/site/ about_bluefi	csbt.org/site/ about_bluefi	ceanhealthin dex.org/Goal	shbase.org/S ummary/Spec	csbt.org/site/ about_bluefi	ccsbt.org/en/ content/total	ccsbt.org/en/ content/total	nvironment.g ov.au/cgi-	ao.org/docre p/005/y2498	csbt.org/site/ about_bluefi
Patagonian toothfish, Australia	fma.gov.au/a bout/legislati	fma.gov.au/fi sheries/macq	ceanhealthin dex.org/Goal	tor.org/stabl e/24864808;	fma.gov.au/fi sheries/macq	fma.gov.au/r esources/cat	fma.gov.au/fi sheries/macq	fma.gov.au/fi sheries/macq	ccamlr.org/e n/system/file	ccamlr.org/e n/system/file
Antarctic toothfish, CCAMLR	ccamlr.org/e n/conservati	ccamlr.org/e n/complianc	argosfroyane s.com/sustai	tor.org/stabl e/24864808;	ccamlr.org/e n/system/file	ccamlr.org/e n/fisheries/t	ccamlr.org/e n/document/	ccamlr.org/e n/system/file	ccamlr.org/e n/system/file	ccamlr.org/e n/system/file
Patagonian toothfish, South Africa	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	argosfroyane s.com/sustai	tor.org/stabl e/24864808;	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	cambridge.or g/core/journ
Patagonian toothfish, UK	ov.gs/fisherie s/legislation/	ov.gs/fisherie s/overview/	sc.org/track- a-	sciencedirect .com/science	ov.gs/gsgssi- consultation	ov.gs/fisherie s/overview/;	ov.gs/fisherie s/overview/;	ov.gs/fisherie s/overview/;	ov.gs/fisherie s/overview/;	ov.gs/environ ment/marine-

VARIABLES	Management										
CRITERIA	Monitoring Compliance System	Certification	Science-based decision making	Foodweb knowledge	Breeding/size protection	Capacity building	By-catch / mortality management	Stock assessments	Stock survey	EBFM	VMS
FISHERIES											
Alaska pollock, USA	afisheries.no aa.gov/sites/	shwatch.gov/ seafood_prof	sc.org/track- a-	shwatch.gov/ seafood_prof	shwatch.gov/ seafood_prof	dfg.alaska.go v/index.cfm?	nt.uaf.edu/no sb/papers/20	afsc.noaa.go v/REFM/Docs	afsc.noaa.go v/REFM/Docs	isheries.noaa .gov/resource	fisheries.noa a.gov/sustain
Anchoveta, Peru	rs/jesnil/App Data/Local/P	rs/jesnil/App Data/Local/P	marpe.pe/im arpe/;	ao.org/fisher y/docs/DOCU	ao.org/fisher y/docs/DOCU	ao.org/fisher y/docs/DOCU	- cdn.com/S01	marpe.gob.pe /imarpe/inde	marpe.pe/im arpe/index.p	marpe.pe/im arpe/index.p	urekalert.org /pub_release
Atlantic seabob, Suriname	cfisu.org/mar ine-	sc.org/track- a-	sc.org/newsr oom/news/su	sc.org/newsr oom/news/re	sc.org/track- a-	sc.org/track- a-	sc.org/track- a-	cfisu.org/mar ine-	sc.org/track- a-	sc.org/newsr oom/news/re	cfisu.org/mar ine-
Cod, Canada	atssa.gov.za/ publications/	atssa.gov.za/ publications/	meslive.co.za /ilive/2013/0	atssa.gov.za/ publications/	shaq.gov.nl.c a/research_d	shaq.gov.nl.c a/research_d	shaq.gov.nl.c a/research_d	shaq.gov.nl.c a/research_d	shaq.gov.nl.c a/research_d	http://www.d fo-	che- search.gc.ca/
Cod, Iceland	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sc.org/newsr oom/news/ic	ace.library.d al.ca/bitstrea	yalsocietypu blishing.org/	yalsocietypu blishing.org/	sheries.is/ma nagement/fis	sheries.is/ma nagement/go	ace.library.d al.ca/bitstrea	ace.library.d al.ca/bitstrea	pedia.org/wi ki/Vessel_mo
Cod, Norway/Russia	sheries.no/ec osystems-	sc.org/track- a-	/track-a- fishery/fisher	sc.org/track- a-	/track-a- fishery/fisher	sheries.no/ec osystems-	sc.org/newsr oom/news/oc	sc.org/track- a-	ontereybayaq uarium.org/c	sheries.no/ec osystems-	pedia.org/wi ki/Vessel_mo
Cod, EU	sciencedirect .com/science	opa.eu/fisher ies/cfp/contr	sc.org/newsr oom/news/fir	mark.silverch air.com/fsq1	azonaws.com /academia.ed	mark.silverch air.com/fsq1	lex.europa.eu /legal-	opa.eu/fisher ies/cfp/contr	es.dk/commu nity/groups/	es.dk/commu nity/groups/	rc.ec.europa. eu/document
Eel, high seas/EU	lex.europa.eu /legal-	opa.eu/fisher ies/cfp/contr	lex.europa.eu /legal-	/news-and- events/Docu	shbase.org/T rophicEco/Pr	lex.europa.eu /LexUriServ/L	lex.europa.eu /legal-	lex.europa.eu /legal-	/news-and- events/Docu	/news-and- events/Docu	pedia.org/wi ki/Vessel_mo
Hake, Peru	ishsource.org /stock_page/	ishsource.org /stock_page/	ishsource.org /stock_page/	ishsource.org /stock_page/	shbase.org/s ummary/146	cations.iadb. org/bitstrea	cations.iadb. org/bitstrea	ishsource.org /stock_page/	ishsource.org /stock_page/	/fis/worldne ws/worldnew	pedia.org/wi ki/Vessel_mo
Hake, South Africa	atssa.gov.za/ publications/	atssa.gov.za/ publications/	sc.org/track- a-	atssa.gov.za/ publications/	sciencedirect .com/science	da.agric.za/d oaDev/sideM	da.agric.za/d oaDev/sideM	atssa.gov.za/ publications/	da.agric.za/d oaDev/sideM	atssa.gov.za/ publications/	aff.gov.za/daf fweb3/Branc
Herring, Iceland	sheries.is/ma nagement/fis	sheries.is/ma nagement/fis	sc.org/track- a-	pringer.com/ article/10.10	elibrary.wile y.com/doi/ful	uroparl.euro pa.eu/RegDat	sheries.is/ma nagement/fis	sheries.is/ma nagement/go	ishsource.org /fishery_page	http://www.h afro.is	pedia.org/wi ki/Vessel_mo
Northern Prawn Fishery, Asutralia	fma.gov.au/m anaging-our-	ies.msc.org/e n/fisheries/	environment. gov.au/syste	siro.au/en/O utcomes/Oce	fma.gov.au/w p-	environment. gov.au/syste	fma.gov.au/s ustainability-	fma.gov.au/r esources/cat	mic.oup.com/ icesjms/artic	environment. gov.au/syste	pedia.org/wi ki/Vessel_mo
Orange roughy, Australia	sh.govt.nz/mi -	www.msc.org	che.googleus ercontent.co	sh.govt.nz/NR /rdonlyres/EF	che.googleus ercontent.co	sh.govt.nz/NR /rdonlyres/EF	che.googleus ercontent.co	che.googleus ercontent.co	fma.gov.au/o range-	che.googleus ercontent.co	port.net/asse ts/uploads/fi
Rock lobster, Australia (TAS)	piw.tas.gov.a u/inter/nsf/	www.msc.org	.tas.gov.au/s ea-fishing-	sciencedirect .com/science	.tas.gov.au/s ea-fishing-	ir.sa.gov.au/f isheries/recr	piw.tas.gov.a u/inter/nsf/	sh.gov.au/rep orts/crustace	.tas.gov.au/s ea-fishing-	mas.utas.edu .au/__data/a	pedia.org/wi ki/Vessel_mo
Rock lobster, Austarlia (WA)	nvironment.g ov.au/marine	msc.org/; http://www.fi	sc.org/track- a-	sciencedirect .com/science	sh.wa.gov.au /Species/Roc	sh.wa.gov.au /Species/Roc	sh.wa.gov.au /Documents/	sh.wa.gov.au /Documents/	sh.wa.gov.au /Species/Roc	sh.wa.gov.au /Species/Roc	pedia.org/wi ki/Vessel_mo
Sardine, Namibia	cbd.int/doc/n bsap/fisherie	; http://www.m	fmr.gov.na/d ocuments/12	sciencedirect .com/science	se.org/Countr y/CountrySu	ao.org/docre p/009/a0312	fmr.gov.na/fe es-and-levies	researchgate. net/publicati	fmr.gov.na/d ocuments/12	fmr.gov.na/d ocuments/12	pedia.org/wi ki/Vessel_mo
Southern bluefin tuna, CCSBT	csbt.org/site/ about_bluefi	csbt.org/site/ monitoring_c	ccsbt.org/en/ content/scien	csbt.org/site/ stock_assess	csbt.org/site/ links.php	csbt.org/site/ about_bluefi	ccsbt.org/en/ content/byca	csbt.org/site/ stock_assess	ccsbt.org/en/ content/scien	mar.csiro.au/ biologging4/	pedia.org/wi ki/Vessel_mo
Patagonian toothfish, Australia	fma.gov.au/fi sheries/macq	ies.msc.org/e n/fisheries/m	ntarctica.gov. au/__data/as	fma.gov.au/p ortfolio-	ccamlr.org/e n/conservati	ccamlr.org/e n/system/file	fma.gov.au/fi sheries/macq	fma.gov.au/fi sheries/macq	fma.gov.au/w p-	fma.gov.au/w p-	pedia.org/wi ki/Vessel_mo
Antarctic toothfish, CCAMLR	ccamlr.org/e n/system/file	ies.msc.org/e n/fisheries/r	sc.org/track- a-	fma.gov.au/p ortfolio-	ccamlr.org/e n/conservati	ccamlr.org/e n/system/file	ccamlr.org/e n/system/file	ccamlr.org/e n/conservati	ccamlr.org/e n/conservati	ccamlr.org/e n/conservati	pedia.org/wi ki/Vessel_mo
Patagonian toothfish, South Africa	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	sciencedirect .com/science	ndiseas.org/e cosystems/pr	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	wf.org.za/wh at_we_do/ma	gov.za/sites/ www.gov.za/f	gov.za/sites/ www.gov.za/f	pedia.org/wi ki/Vessel_mo
Patagonian toothfish, UK	ov.gs/docsar chive/legislat	gov.gs/docsa rchive/Fisher	gov.gs/docsa rchive/Fisher	sciencedirect .com/science	gov.gs/docsa rchive/Fisher	gov.gs/docsa rchive/Fisher	gov.gs/docsa rchive/Fisher	gov.gs/docsa rchive/Fisher	gov.gs/docsa rchive/Fisher	sc.org/track- a-	ccamlr.org/e n/system/file

Appendix 4: Fisheries Governance Survey, with responses

Responses to the fisheries governance survey are presented in the order the questions appeared in the survey instrument. I have read the information above and consent to participate in this study. I am over the age of 18 years. Answer	Response	%
Yes	188	100%
No	0	0%
Total	188	100%

Q1. Threats to the marine environment: For each of the potential marine threats, please tell if you believe there is no threat, a minor threat or a major threat.

1.1. No threat

Question	National fisheries	World fisheries	Total Responses
Pollution sourced from land	9	4	13
Eutrophication	19	16	35
Anoxic events	23	20	43
Ocean acidification	14	8	22
Introduced species & pests	5	5	10
Dead marine zones	25	14	39
Energy exploration (	33	21	54
Ecosystem shifts	11	5	16
Habitat destruction	8	0	8
Plastics in the oceans	23	12	35
Coastal development	14	16	30
Overfishing	12	0	12
Climate change	6	3	9
IUU fishing	9	1	10

1.2. Minor threat

Question	National fisheries	World fisheries	Total Responses
Pollution sourced from land	83	65	148
Eutrophication	95	76	171
Anoxic events	95	78	173
Ocean acidification	79	61	140
Introduced species & pests	91	79	170
Dead marine zones	92	83	175
Energy exploration (oil, gas etc)	87	84	171
Ecosystem shifts	74	63	137
Habitat destruction	57	41	98
Plastics in the oceans	94	62	156
Coastal development	75	61	136
Overfishing	49	32	81
Climate change	63	46	109
IUU fishing	40	14	54
Other, please specify	4	5	8

1.3. Major threat

Question	National fisheries	World fisheries	Total Responses
Pollution sourced from land	78	98	176
Eutrophication	56	65	121
Anoxic events	48	53	101
Ocean acidification	65	96	161
Introduced species & pests	72	78	150
Dead marine zones	46	63	109
Energy exploration (oil, gas etc)	45	63	108
Ecosystem shifts	78	97	175
Habitat destruction	98	123	221

Plastics in the oceans	49	87	136
Coastal development	76	85	161
Overfishing	103	141	244
Climate change	95	119	214
IUU fishing	47	86	133
Other, please specify	13	19	32

Q2. In your experience, what are the three main challenges of managing fisheries? Please add a brief description.

Answer	Response	%
Lack of political will	98	56%
Not all stake holders are involved	34	20%
Not enough compliance with regulations	57	33%
Fisheries are very complex to manage	29	17%
International cooperation is needed	25	14%
Over-fishing	51	29%
Lack of knowledge in fish behaviour	11	6%
High amounts of by-catch and discard	30	17%
Poverty	14	8%
Stock assessment & monitoring	49	28%
Need to track trading of fish products	12	7%
Growing human population (food security)	22	13%
Take high levels of uncertainty into account when setting quotas	12	7%
Ecosystem management	24	14%
Consider socio-economic implications in poorer regions	21	12%
Impacts of climate change	20	11%
Amount of IUU fishing is underestimated	37	21%
Stakeholder agreements	19	11%
Other	39	22%

Q3. In what country do you work? .

Answer	Response	%
Argentina	2	1%
Australia	40	24%
Bangladesh	1	1%
Canada	5	3%
China	1	1%
Czech Republic	1	1%
Denmark	1	1%
France	4	2%

Germany	2	1%
Greece	1	1%
Iceland	4	2%
India	1	1%
Indonesia	2	1%
Ireland	1	1%
Italy	3	2%
Japan	3	2%
Kenya	1	1%
Mexico	3	2%
Mongolia	1	1%
Namibia	5	3%
Netherlands	3	2%
New Zealand	2	1%
Nigeria	5	3%
Norway	2	1%
Philippines	2	1%
Saudi Arabia	1	1%
South Africa	5	3%
Spain	1	1%
Sweden	8	5%
Tanzania	1	1%
Turkey	2	1%
Uganda	1	1%
United Kingdom	30	18%
United States	21	12%
Total	170	100%

Q4. What is your role in fisheries?

Answer	Response	%
Fisheries manager / Natural resource manager	14	8%
Fisher	31	18%
Policy maker	13	7%
Scientist	96	54%
NGO member	5	3%
Other, please specify	18	10%
Total	177	100%

Q5. Where do you work?

Answer	Response	%
National management	40	34%
Sub-national management	15	13%
Community/Communal/Indigenous	2	2%
International	28	24%
University	17	15%
Other, please specify	15	13%
Total	117	100%

Q6. What position/level do you work at now?

Answer	Response	%
Field management	28	19%
Middle management	50	34%
Senior management	51	35%
Executive management	17	12%
Total	146	100%

Q7. What fishery or fisheries are you involved in? If you work with several fisheries, please pick one fishery. Should you wish to give information about more than one fishery, please take the survey again.

Answer	Response	%
Large pelagic	23	16%
Small pelagic	22	15%
Large demersal	36	25%
Small demersal	10	7%
Crustaceans	17	12%
Shellfish	2	1%
Inland fishery	3	2%
Aquaculture	4	3%
Coastal	12	8%
Shark	1	1%
Other	13	9%
Total	143	100%

Q8. How would you best describe the fishery you work in?

Answer	Response	%
Collapsed	10	6%
Highly over-fished	15	9%
Over-fished	49	28%
Sustainably fished	67	39%

Recovering	14	8%
Developing / exploratory	4	2%
No information	13	8%
Total	172	100%

Q9. How many years of experience do you have in fisheries?

Answer	%
0-3 years	16%
3-5 years	10%
5-10 years	11%
10-15 years	14%
15-20 years	17%
20-25 years	17%
More than 25 years	15%

Q10. What are the major changes that have occurred in fisheries management during your career with fisheries? Multiple answers possible.

Answer	Response	%
There are no major changes	8	7%
Increased level of scientific input	60	55%
Increased level of industry input	53	49%
Increased level of NGO input	47	43%
Environmental versus fisheries department	40	37%
Level of collaboration amongst stake holders and organizations	51	47%
Increased number of staff	8	7%
Increased number of scientists	26	24%
Amount of resources (money, staff)	18	17%
Ecosystem based management instead of single species management	50	46%
Dealing with pollution (e.g. terrestrial run-offs like fertilizer, soil turbidity)	16	15%
Other, please specify	20	19%

Q11. In the last 5-10 years, have resources (such as funding, staff, research, equipment) for management overall:

Answer	Response	%
Increased a lot	5	4%
Increased a little	49	39%
Stayed about the same	35	28%
Decreased a little	25	20%
Decreased a lot.	12	10%
Total	126	100%

Q.12. Has the fishery you work with implemented Ecosystem-Based Fisheries Management (EBFM) or a similar holistic approach to governing fisheries?

Answer	Response	%
Yes	104	60%
No	68	40%
Total	172	100%

Q13. How well do you consider the over-all implementation process of EBFM, or similar management approach, has been?

Answer	Response	%
Very successful	11	10%
Successful	32	30%
Neutral	50	47%
Unsuccessful	13	12%
Very unsuccessful	1	1%
Total	107	100%

Q14. How satisfied are you with the Ecosystem Based Fisheries Management process?

Question	Very satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied	Total Responses
Planning process	11	47	33	9	4	104
Implementation process	8	40	30	23	3	104
Results	7	26	45	21	4	103

Q15. Briefly describe your experience with the implementation of EBFM.

Answer	Response	%
It still doesn't consider the whole ecosystem	30	36%
Lack in scientific knowledge delays proper implementation	19	23%
Highly complex procedure, which makes it hard to really implement EBFM	48	58%
Lack of compliance to secure successful EBFM	22	27%
Time consuming	19	23%
Difficult to decide what variables and what spp should be considered as there are so many variables and spp in an ecosystem	28	34%
Insufficient compliance	10	12%
It has worked very well	6	7%
Improvements can already be seen	15	18%
It has been a satisfactory process	11	13%
Other	11	13%

Q16. How do you view the role of governance and management to fisheries in your country as well as world-wide? For each of the following variables, please say if you believe there is a need for more or less.

16.1. Highly needed

Question	National fisheries	World fisheries	Total Responses
Stronger political will to manage fisheries	98	131	229
Improved conservation measures	68	107	175
Enforcement of regulations	69	112	181
Change of governance structure	57	86	143
More money	59	81	140
More staff	51	74	125
More research	71	98	169
More international collaboration	83	116	199
Managing Illegal, Unreported & Unregulated fishing (IUU)	76	128	204

16.2. Somewhat needed

Question	National fisheries	World fisheries	Total Responses
Stronger political will to manage fisheries	36	27	63
Improved conservation measures	56	46	102
Enforcement of regulations	50	39	89
Change of governance structure	58	55	113
More money	76	63	139
More staff	70	59	129
More research	65	51	116
More international collaboration	48	31	79
Managing Illegal, Unreported & Unregulated fishing (IUU)	47	30	77

16.3. Satisfactory as it is

Question	National fisheries	World fisheries	Total Responses
Stronger political will to manage fisheries	19	5	24
Improved conservation measures	28	4	32
Enforcement of regulations	38	9	47
Change of governance structure	35	11	46
More money	28	10	38
More staff	38	19	57
More research	23	8	31

More international collaboration	21	9	30
Managing Illegal, Unreported & Unregulated fishing (IUU)	32	3	35

16.4. Less needed

Question	National fisheries	World fisheries	Total Responses
Stronger political will to manage fisheries	8	3	11
Improved conservation measures	10	3	13
Enforcement of regulations	3	1	4
Change of governance structure	8	1	9
More money	3	2	5
More staff	6	2	8
More research	3	0	3
More international collaboration	7	2	9
Managing Illegal, Unreported & Unregulated fishing (IUU)	1	0	1

Q17. Why do you believe, on a global scale, we are still facing fisheries over-exploitation in regulated fisheries? Drag & drop your rankings.

Question	Major challenge	Some challenge	Minor challenge	No challenge	Total Responses
There is not enough scientific information.	43	74	40	4	161
Scientific knowledge is not being used to its fullest.	90	49	21	2	162
Lack of political will.	133	25	10	0	168
There needs to be stricter laws and regulations.	74	63	24	4	165
There needs to be more compliance and enforcement of laws.	109	45	11	1	166
Management is focused on species rather than eco-based management.	81	58	20	5	164
General public does not care enough about sustainable fishing to make it worthwhile for politicians to make it a priority.	68	60	31	7	166
Fish abundance is too complex to predict.	39	70	50	7	166
Lack of formal harvest strategies	44	66	45	7	162

Environmental variables affecting fisheries abundance are too complex to measure and predict.	50	66	39	9	164
Commercial fishers have too much influence.	54	62	31	16	163
There is not enough scientific expertise to interpret scientific data on management level.	47	54	50	13	164
Lack of political knowledge on marine and fisheries related issues.	87	55	17	3	162
Other	18	2	0	0	20

Q18. What management tools are being and should be used to manage the fishery you work in?

Question	Tools being used	Tools that should be used	Total Responses
Total Allowable Catch (TAC)	116	53	169
Individual Transferable Quota (ITQ)	66	47	113
Seasonal closures	104	68	172
Regional zoning	66	46	112
Spatial closures (e.g. MPA)	95	63	158
Spawning closures	69	60	129
Size limits	99	70	169
Commercial only fishing areas	19	23	42
Recreation only fishing areas	23	28	51
Ecosystem based management	67	73	140
Bag limits	38	36	74
Mesh size	75	53	128
Trawling net size restrictions	59	34	93
Fishing vessel size restriction	38	25	63
Horsepower restrictions	26	20	46
Tabu / Taboo	9	9	18
Bottom trawling is banned	34	33	67
Other gear restrictions	65	29	94
Fishing vessels buy backs by government	16	15	31
Fuel subsidies	35	18	53
Surplus fish purchases	11	22	33
Grants for new fishing vessels	18	12	30
Tax exemption programs	13	14	27
Vessel construction, renewal and modernization	20	15	35
Fishing access agreements	25	23	48

By-catch reduction device	59	46	105
Other	9	13	22

Q19. In your work, who is and who should be involved in the fisheries management process?

Question	Who is involved?	Who should be involved?	Total Responses
Fisheries managers	148	86	234
Natural resource managers	75	80	155
Fishers	103	103	206
Politicians	130	67	197
Scientists	133	95	228
NGOs	80	78	158
The public	35	69	104
Local communities	36	79	115
Other	3	6	9

Q20. Here is a range of input controls used in fisheries management. Do you support / oppose the concept of:

Question	Strongly support	Support	Neutral	Oppose	Strongly oppose	Total Responses
Gear restrictions	105	43	16	1	1	166
Vessel size restrictions	51	40	38	30	4	163
Horsepower restrictions	38	35	50	35	5	163
Seasonal closures	107	45	12	2	0	166
Regional zoning	87	47	25	3	0	162
Recreational only fishing areas	42	33	56	24	6	161
Spatial closures	105	47	12	1	0	165
Spawning closures	109	37	14	1	0	161
Size limits	100	42	20	2	1	165
Commercial only fishing areas	38	36	58	28	0	160
BRDs (by-catch reduction device)	100	48	12	2	0	162

Q21. There is a range of output controls used in fisheries management. Do you support / oppose the concept of:

Question.	Strongly support	Support	Neutral	Oppose	Strongly oppose	Total Responses
Total Catch Limits (TACs)	100	43	22	2	1	168
Individual Transferable Quotas (ITQ)	75	41	40	7	5	168
Bag limits	71	44	45	4	1	165

Q22. In your experience in fisheries, do you support / oppose the concept of:

Question	Strongly support	Support	Neutral	Oppose	Strongly oppose	Total Responses
Fishing vessels buy backs by government	40	64	30	25	9	168

Fuel subsidies	33	19	26	36	52	166
Surplus fish purchases	13	30	50	38	34	165
Grants for new fishing vessels	31	21	30	35	50	167
Tax exemption programs	29	26	36	31	44	166
Vessel construction, renewal and modernization	34	43	39	16	35	167
Fishing access agreements	57	61	38	7	4	167

Q23. How much do you estimate the fishery you work with costs to manage annually (US dollar)? Costs include research, management, subsidies.

Answer	Response	%
< US$500,000	11	7%
US$500,000 - 1 million	18	11%
US$1 million - $2 million	6	4%
US$3-5 million	16	10%
US$6-15 million	6	4%
US$16-20 million	6	4%
US$21-30 million	1	1%
US$31-40 million	1	1%
US$41-50 million	1	1%
US$51-60 million	2	1%
US$61-70 million	1	1%
US$71-80 million	0	0%
US$81-90 million	2	1%
US$91-100 million	2	1%
US$101-150 million	1	1%
US$151-200 million	2	1%
US$200-250 million	1	1%
>US$ 250 million	4	2%
Local currency, if you wish	0	0%
Don't know	86	51%
Total	167	100%

24. Do you know how much revenue your fishery provide annually?

Answer	Response	%
Yes	39	31%
No	87	69%
Total	126	100%

Q25. How many fishing vessels operate within your fishery?

Answer	Response	%
1-5	19	13%
6-25	33	23%
26-50	22	15%
51-75	13	9%
76-100	5	4%
>100	50	35%
Total	142	100%

Q26. How many fishing vessels are registered in the country where you work?

Answer	Response	%
1-10	5	9%
11-30	1	2%
31-60	2	4%
61-100	2	4%
101-200	3	5%
201-400	3	5%
401-600	6	11%
601-1000	2	4%
1,001-2,000	8	14%
2,001-5,000	9	16%
5,001-10,000	5	9%
10,001-20,000	7	13%
>20,000	3	5%
Total	56	100%

Q27. In your country, how important is fishing as a main food source of protein?

Answer	Response	%
Overall survival depends on fishing	12	7%
Vital for some regions/areas	39	23%
Somewhat important	46	27%
Not important for survival	71	42%
Total	168	100%

Q28. In your country, how important is fishing as a main source of income?

Answer	Response	%
Overall income depends on fishing	8	5%
Vital for some regions/areas	70	42%

Somewhat important	61	37%
Not important for income	27	16%
Total	166	100%

Q29. In your country, are there regions where fishing is the major economic activity?

Answer	Response	%
Yes, many regions	29	18%
Yes, a few regions	107	65%
Yes, one region	5	3%
No	24	15%
Total	165	100%

Q30. In your country, are there regions or areas where fishing is the major food source of protein?

Answer	Response	%
Yes	68	41%
No	96	59%
Total	164	100%

Q31. Are subsidies provided for fishers in the country in which you work (including fuel rebates, low interest loans, employment, buy-backs, reduced tax)? .

Answer	Response	%
Yes	87	52%
No	56	34%
Don't know	23	14%
Total	166	100%

Q32. What type of subsidies are there?

Answer	Response	%
Fuel	75	88%
Lower interest on bank loans	22	26%
Employment payments from the government	30	35%
Cultural subsidies	13	15%
Other, please specify	22	25%

Q33. Do you believe these subsidies contribute to overcapacity of the fishing industry?

Answer	Response	%
Not at all	28	32%
Somewhat	34	39%
Significantly	22	25%
Don't know	3	3%

Total	87	100%

Q34. Who should carry the real cost of fish products? Costs include governance, management, research and monitoring of fisheries.

Answer	Response	%
Fishers	113	69%
Consumers	112	69%
Government	104	64%
Don't know	14	9%

Q35. The fishery I work with has:

Answer	Response	%
A single species management approach	57	37%
An ecosystem management approach	87	56%
Don't know	12	8%
Total	156	100%

Q36. In your experience with fisheries, which 5 (if any) fisheries management and governance regulations are the most efficient for Ecosystem Based Fisheries Management?

Answer	Response	%
FAO code of conduct	7	6%
MPAs	63	52%
ITQs	59	49%
Gear restrictions	56	46%
Stakeholder participation	43	36%
Good science	64	53%
Co-management	30	25%
Closures	28	23%
No bottom trawling	25	21%
Stakeholders' education	23	19%
Size limits	10	8%
More legislation	8	7%
Assessment of implementations	25	21%
Spawning closures	11	9%
Mesh size	11	9%
TAC	31	26%
Monitoring	30	25%
By-catch Reduction Device (BRD)	35	29%
Other	20	17%

Q37. What type of organisation do you believe would be optimal to ensure successful Ecosystem Based Fisheries Management (or the alike management)?

Answer	Response	%
Top-down management (centralised governance)	11	7%
Bottom-up management (communal, local)	13	8%
Mix of top-down and bottom-up management	132	83%
Don't know	7	4%

Q38. Decision making process; information and decisions. For the following statements, please indicate if you agree or disagree.

Question	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Total Responses
In your role, the scientific information is easy to understand, interpret and apply.	23	74	18	47	2	164
You have an appropriate amount of information (scientific or otherwise) to make sound fisheries management decisions.	27	63	38	31	4	163
You consider there are robust mechanisms to deal with assessing uncertainty.	13	64	29	56	2	164
You believe you can influence final fisheries management decisions.	15	65	27	40	16	163
You believe the current decision making process of your fishery is adequate for sustainable fisheries.	10	57	28	50	17	162
Do you believe the current decision making process of your fishery is adequate for an overall sustainable marine biodiversity?	10	45	34	56	17	162
Comment	1	1	0	2	1	5

Q39. What information or decision-making processes would you like to see more of when making fisheries or ecosystem management decision?

Answer	Response	%
Use of indicators in decision-making process	31	21%
More research about ecosystem processes and functions	41	28%
Politicians need to understand the science	62	42%
All stake-holder involvement	56	38%
Industry compliance of regulations	23	16%
Supporting fishers with knowledge and implementation of regulations	23	16%
Holistic objectives; marine & socioeconomic issues	34	23%
Use EBFM models	29	20%
Decreasing IUU fishing	28	19%

Integrating fishing and environmental policies	44	30%
Political commitment	52	36%
Management transparency	56	38%
Other	13	9%

Q40. What variables are considered and should be considered when setting fisheries quotas?

Question	Variables that are considered	Variables that should be considered	Total Responses
Size structure of the stock	117	81	198
Age structure of the stock	101	81	182
Catch data	122	73	195
Catch Per Unit Effort (CPUE)	106	67	173
Life history traits	60	86	146
Maximum Sustainable Yield	80	68	148
Maximum Economic Yield	37	52	89
Climate change	23	101	124
Recruitment	90	92	182
Abundance	104	71	175
Mortality	94	73	167
Effects on the ecosystem	41	103	144
Other, please specify	7	16	23
Other, please specify	2	4	6
Other, please specify	2	2	4
Don't know	5	3	8

Q41. If any, what resources would you like to have more of in order to improve sustainable fisheries and marine biodiversity?

Answer	Response	%
Resources are already adequate	15	9%
Scientific knowledge	107	65%
Enforcement mechanisms	75	45%
Legal expertise & advice	35	21%
Collaboration amongst stake holders	105	64%
Collaboration amongst governmental departments	81	49%
Administration staff	10	6%
Other, please specify	20	12%

Q42. How would you assess management of the fishery you are involved in?

Question	Strongly agree	Agree	Neutral	Disagree	Strongly disagree	Total Responses
Current management is sufficient to ensure the long-term sustainability of fishery	19	55	20	50	16	160
There needs to be stricter regulations on commercial fishing	25	46	29	50	9	159
There needs to be stricter regulations on recreational fishing	17	37	53	41	12	160
Current commercial fishing regulations are adequately enforced	14	53	29	49	17	162
Current management is sufficient to ensure the long-term sustainability of overall biodiversity	14	30	31	65	21	161
There are too many regulations	8	33	34	74	10	159
The regulations are too complex to manage, monitor and measure successfully	12	35	28	70	13	158

Q43. I would like to get some information on how satisfied you are with various aspects of your job. How satisfied are you with:.

Question	Very satisfied	Satisfied	Neutral	Dissatisfied	Very dissatisfied	Total Responses
Level of access you have to scientific fishing data	27	80	17	37	4	165
Number of other managers working with you	11	54	61	29	1	156
Resources to manage in the best way you know	11	46	47	44	6	154
Collaboration with scientists	25	73	20	40	3	161
Getting messages across to the decision makers	7	37	28	70	20	162
Decisions based on scientific expertise	8	54	31	56	14	163
Level of influence you have on decision making	7	43	34	64	15	163
Level of application of your work	14	50	42	41	12	159

Q44. Do you believe that illegal, unreported and unregistered (IUU) fishing is a problem for your fishery?

Answer	Response	%
Yes	100	64%
No	57	36%
Total	157	100%

Q45. How much of the total catch in your fishery do you believe is due to illegal, unreported and unregistered fishing?

Answer	Response	%
None at all	4	4%
Less than 5%	11	11%
6-15%	20	21%
16-30%	21	22%
31-40%	14	15%
41-50%	15	16%
51-60%	6	6%
61-80%	0	0%
More than 80%	5	5%
Total	96	100%

Q46. Do you believe that illegal, unreported and unregistered (IUU) fishing is a problem within your country?

Answer	Response	%
Yes	107	66%
No	55	34%
Total	162	100%

Q47. How much of the total catch in your country do you believe is due to illegal, unreported and unregistered (IUU)?

Answer	Response	%
None at all	0	0%
Less than5%	7	7%
6-15%	23	22%
16-30%	39	38%
31-40%	13	13%
41-50%	13	13%
51-60%	3	3%
61-80%	3	3%
More than 80%	3	3%
Total	104	100%

Q48. Do you believe that illegal, unreported and unregistered (IUU) fishing is a problem in some parts of the world?

Answer	Response	%
Yes	137	99%
No	1	1%
Total	138	100%

Q49. How much of the total catch world-wide do you believe is due to illegal, unreported and unregistered (IUU)?

Answer	Response	%
None at all	0	0%
Less than5%	0	0%
6-15%	3	2%
16-30%	25	19%
31-40%	36	27%
41-50%	32	24%
51-60%	19	14%
61-80%	15	11%
More than 80%	4	3%
Total	134	100%

Q50. What are the key aspects of these IUU problems?

Answer	Response	%
Corruption	80	66%
Lack of data	53	44%
Poverty	52	43%
No or little governance in place	61	50%
No or little high seas controls	52	43%
Lack of international policies	34	28%
Lack of international compliance	46	38%
Fishers' data not accurate	57	47%
Growing human population	34	28%
Lack of political will	61	50%
Trawlers entering MPAs	11	9%
High demand for high-valued fish species	24	20%
Recreational fishers	11	9%
Large black market	34	28%
Insufficient compliance	67	55%
Not enough awareness of the consequences	19	16%

Habitat destruction	23	19%
Other	7	6%

Q51. What approaches does your organisation use to measure fish abundance?

Answer	Response	%
No measures are used	10	6%
Catch Per Unit Effort (CPUE)	103	65%
Size	75	47%
Recruitment	58	36%
Fishers' log books	100	63%
Government trawling data	61	38%
Age structure	66	42%
Other, please specify	31	19%

Q52. What improvements are needed to obtain/maintain sustainable fisheries?

Answer	Response	%
No improvements are needed	10	6%
Stronger political commitment to marine ecosystem management is needed	119	72%
More regulation is needed	38	23%
More science is needed	88	53%
More enforcement is needed	96	58%
Higher reliability and quality of catch data is needed	85	52%
A higher level of ecosystem management is needed	88	53%
Consumers drive the market and are responsible for buying sustainable seafood	61	37%
Other	12	15%

Q53. How old are you?

Answer	Response	%
18-25	7	4%
26-34	31	19%
35-54	99	60%
55-64	25	15%
65 or over	3	2%
Total	165	100%

Q54. What is the highest level of education you have completed?

Answer	Response	%
Less than High School	0	0%
High School / GED	8	5%
Some College	6	4%
2-year College/University Degree	8	5%
3-4-year College/University Degree	24	14%
Masters Degree	47	28%
Doctoral Degree	71	42%
Professional Degree (JD, MD)	4	2%
Total	168	100%

Q55. What is your degree in?

Answer	Response	%
Marine science	89	59%
Environmental science	30	20%
Business & Management	11	7%
Economics	4	3%
Law	4	3%
Political science	5	3%
Social science	5	3%
Other (please specify)	10	7%

Q56. What is your gender?

Answer	Response	%
Female	47	29%
Male	117	71%
Total	164	100%

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Fisheries sustainability relies on biological understanding, evidence-based management, and conducive industry conditions

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This article recognizes that the impacts and effects of fishing are key to marine ecosystem management and explores the relationship between fisheries exploitation and sustainable harvests, and the collapse and depletion of stocks. A survey of 21 fisheries from around the world assessed key biological, environmental, social, economic, industry, governance, and management variables and associated criteria that potentially affect stock abundance. We developed 51 criteria as potential contributing factors underpinning three main fishery management outcomes: a sustainable fishery, a depleted fishery, or a collapsed fishery. The criteria that scored highest for the 15 sustainable fisheries in the analysis were associated with the broad groupings of biology (characteristics of the species and stock), management (legal and policy frameworks, tools and decision systems), and industry (economic performance and value). This analysis showed that while a fishery might have a high score for management, sustainability is likely to be difficult to achieve without a medium or high score for biological knowledge.

Keywords: ecosystem-based fisheries management, fisheries exploitation, marine conservation, meta-analysis, ocean governance, sustaining fisheries

Introduction

Ecosystem-based management of marine systems is challenging. This is because of system complexity, a high degree of connectivity among elements, non-linear responses of these elements to environmental drivers and stressors, and difficulties associated with monitoring ocean processes. Marine ecosystems are subject to a range of anthropogenic impacts, including the impacts of fishing, which underpin rapid rates of biodiversity change and major shifts in marine ecosystems (Diaz and Rosenberg, 2008; Rockström, 2009; Duarte, 2014; FAO, 2016). Fishing has direct and indirect consequences on predator/prey relationships in an ecosystem, potentially causing cascading effects (Myers *et al.*, 2007). Excessive fishing pressure may lead to both depleted fisheries where stocks may be overfished or, in extreme cases, collapse (with catches reduced to less than 10% of the maximum historical catch) (Worm *et al.*, 2009). This is not new phenomena as several fish stocks had collapsed by the 1930s (Jackson *et al.*, 2001), but rapid development of large-scale industrial fishing after the Second World War has hastened exploitation of global fisheries (Myers and Worm, 2003). In the past decade, a number of analyses have shown that approximately a third of the world's exploited fish stocks are depleted to unsustainable biomass levels (i.e. overfished) (Worm *et al.*, 2009; Costello *et al.*, 2012; FAO, 2016). These studies show that on-going policy commitments and management efforts are required in national and international waters to secure sustainable harvest of marine fisheries into the future.

Considerable attention has been given to tools and approaches that will predict at which abundance level a fish stock is threatened by collapse or extinction (Myers *et al.*, 1995; Cook *et al.*, 1997; Carlton *et al.*, 1999; Halpern *et al.*, 2008a; Hutchings *et al.*, 2010). Studies of stock recovery show that reversal of a long-term decline in fish abundance is typically a slow process, with rate of recovery dependent on many factors, especially life history—such as the age of maturity (Hutchings and Reynolds, 2004;

Hutchings, 2005). The long time frames involved create additional cognitive and political challenges for managers struggling with recovery of depleted stocks (Costello *et al.*, 2016). A key question is, therefore, given the effort directed at fisheries management, why is it that so many fisheries are collapsed or overfished?

This article accepts the premise that understanding the impacts and effects of fishing are key to sustainable marine resource management and the sustainability of marine ecosystems (Pauly *et al.*, 1998; Moffitt *et al.*, 2016; Walters *et al.*, 2016; Melnychuk *et al.*, 2017). Here, we explore 21 commercial fisheries and explore the relationship between fisheries exploitation and sustainable harvests, and the collapse and recovery of stocks. We accept that the focus on a set of data-rich commercial fisheries is a potential limitation, but consider that it is an acceptable compromise since analysis of data-rich fisheries enables identifying the key factors affecting the sustainability of stocks.

Methods and background

General study design

Studies of the world's fisheries are only possible where data are freely available, noting that existing data may be incomplete (e.g. it may exclude by-catch and discards). Patchiness in available data has constrained status assessments for many fisheries around the globe. Moreover, most published studies that do try to assess the global status of fisheries do not consider or integrate ecological, legal, regulation, economic, and social aspects. Few have attempted to identify specific sets of characteristics that distinguish sustainable fisheries from those that have collapsed. Nor have they identified criteria that may indicate, *a priori*, fisheries that are prone to collapse. Here we aim to do just that—to identify the multidisciplinary set of variables and criteria, alone or in combination, that indicate whether a fishery is likely to be sustainable, depleted, or collapsed.

We assigned fisheries status based on definitions established for this exercise rather than relying on national assessments and definitions that often differ from fishery to fishery. For the purposes of this study, the following definitions are used:

- A *sustainable* fishery is where fishing pressure is at or less than F-targ and the stock size is around its target reference point level, i.e. long-term depletion due to overfishing has either not occurred or the stock has fully recovered from past excessive exploitation.
- A fishery was categorized as *depleted* when the stock had dropped below the target reference point (F-targ) for the fishery, which is typically set or assumed to be maximum sustainable yield (MSY). We appreciate that stocks may dip into this zone via environmental variation, but in the main species considered here were in this state due to prolonged overfishing (excessive fishing pressure leading to depletion of the stock) and so the term is appropriate as a shorthand reference.
- A fishery was categorized as *collapsed* when the stock(s) had been fished until the biomass was depleted to <20% of unfished biomass levels, which is taken as the proxy limit reference point for stocks in Australia; beyond this point no targeted fishing pressure should be applied.

While we acknowledge that stock status is a continuum, it is standard fisheries practice to classify stocks into a few small classes—such as sustainable or over exploited. The general concept of these classes is similar across jurisdictions, however, the devil is in the detail—with explicit definitions differing between countries (for example). Consequently, we assigned fisheries status based on definitions established for this exercise rather than relying on national assessments and definitions that often differed from fishery to fishery.

The selected six variables and their 51 associated criteria (Table 1, Supplementary Material S1 and S2) have individually been considered in detail by a large number of researchers around the world, and introduced and evaluated in peer-reviewed scientific journals over the past four decades. Multidisciplinary synthesis using subsets of these criteria have been rare, but it is necessary to bring the complete suite together to understand the highly complex nature of fisheries science and management. This is because understanding the interrelations amongst the six classes of variables and their criteria is likely to be key to appreciating the full complexity of marine systems, the fisheries they support, and means of governance and management that achieve sustainably. The variables are explained in detail in Table 1. The reference time period for the study was 2011–2016 (Supplementary MaterialS2 and S3).

In addition to the data collection, an "expert elicitation" approach was used as a method of verification of each case study (discussed further below). After the project team had scored the fisheries based on publicly available information and the criteria outlined in Table 1, experts on each fishery were approached to check the ratings or to highlight where these may be in error and require correction. Experts are defined as people with broad expertise and skills in analytical judgement together with essential knowledge of a given subject (Burgman *et al.*, 2011). This method has been widely used to collect data in the natural and social sciences (Lenton *et al.*, 2008; Choy *et al.*, 2009). In this research, we called upon stock assessment scientists and fisheries managers who had close involvement in and/or knowledge of a fishery. Each of the experts have at least a master's degree in marine science and have been working with the specific fishery for a minimum of 4 years. At least one expert per fishery was engaged and these experts commented on each of the six variables and the 51 criteria. A glossary of terms was provided to ensure all criteria were understood (Table 1). The identity of the experts is confidential (as required by the ethics rules under which the work was conducted).

Scoring criteria

A mixed method research approach was used to better understand the complexity of sustainable, depleted, and collapsed fisheries. A qualitative scaling method was used when evaluating the status of each criterion for each case study location, viz. 2 = potential positive impact on the fish stock, 1 = potentially some positive impact on the stock, 0 = potential negative impact on the stock. Note also that where no or insufficient data were available, a criterion was scored as zero on the basis of applying a precautionary approach. In the relevant Supplementary Material, criteria scored as "0" for reasons of no or insufficient data are indicated, and represent only 8% of cases with a zero score. Given there were a different number of criteria for each variable, aggregate scores were created for each variable (via simple addition of the criteria scores) and then rescaled so that all the aggregate indices were scored on a scale of 1–5. This meant that to achieve a

Table 1. Key variables and scoring used for the analysis of fisheries.

	Criteria	Score 2	Score 1	Score 0
Variable 1—Biology				
A core challenge in fisheries management is defining which ecological indicators to use when estimating a stock's carrying capacity, so that long-term sustainable catch limits can be set in an ecosystem-based context (Fulton *et al.*, 2005; Welsford, 2011; FAO, 2016; Melnychuk *et al.*, 2017). Understanding and modelling stock abundance and many variables effecting this abundance, such as food–web relationships, habitat, birth, death, and migration, including age/size structure is clearly a demanding task (Schaefer, 1954; Wilderbuer and Zhang, 1999; Fulton *et al.*, 2014, 2016).	Breeding	Fast growing/early breeders	Slow growing/late breeders	–
	Migratory	No/little migration	Migratory	–
	Fecundity	High recruitment	Low recruitment	–
	Diet specialization	No special diet	Special diet	–
	Age/size distribution	Viable age/size distribution for sustainable stock; distribution that is healthy and can remain productive	No viable age/size distribution for sustainable stock	–
	Habitat specialization of life stages	Particular habitat specialization during some life stages	No habitat specialization	–
	Spatial connectivity	Larvae dispersal	No/low larvae dispersal	–
Variable 2—Environment				
During the last 40 years, much effort has been spent on trying to understand all the biophysical processes involved in the marine world, including physics, connectivity, chemistry, habitat, networks, recruitment, and interactions of prey and predators in food webs (Young *et al.*, 2007; Rockström *et al.*, 2009). Apart from anthropogenic pressures, natural variability such as oceanographic drivers of oxygen and salinity levels also have an effect on biological processes including food supply, reproduction, fecundity, connectivity, and survival rates (Cury *et al.*, 2008).Failure to understand processes and relationships has been seen to cause major ecosystem shifts in food webs (Hughes *et al.*, 2005; Crowder and Norse, 2008; Curtin and Prellezo, 2010; Fulton, 2016).	Ocean Health Index (OHI)	Healthy (90 and above)	Medium health (80–89)	Low health (<80)
	Clean Waters (OHI)	Low contaminated (>90)	Medium contaminated (80–89)	High contamination (<80)
	Carbon storage	>80	60–80	<60
	Anthropogenic influence on habitat (fishing, pollution)	Low/absent	High	Very high
	Disease/virus/toxic algae blooms/invading spp	Little	High	Very high
	Acidification	No effect (fish)	Effect (calcification, crustaceans, mainly)	–
	Hot spot area (climate change	No hotspot area	Hotspot area	–
	Climate variability	No regular impact	Some impact	Regular impact
Variable 3—Social and economic				
One universal dilemma is the increasing size of the human population and the way we need to feed more than 9 billion people by 2050 (FAO, 2016). Around 60% of the world's population live within 100 km of the coast; land-based pollution contributes 80% of all marine pollution; 300 million people are directly dependant on fishing, and 90% of those are coastal small-scale fishers (FAO, 2016; UN, 2016). In 2014, global capture from marine waters was 81.5 million tonnes with a global fishing fleet of 4.6 million vessels (FAO, 2016). The cultural and well-being aspects of the loss from ecosystem services are also drivers in the challenge of conserving nature (McCauley, 2006).	Human Development Index (HDI)	Developed nations (0.75–0.9)	Developing nations (0.74–0.5)	Underdeveloped nations (<0.4)
	Coastal livelihoods and economies (from OHI)	Increased economics	No economic development	Decreased economic development, or no info
	Poverty and Economic Decline Index	Low decline (<1.6)	Medium decline (1.7–5.5)	High decline (>5.5)
	Education Index	>0.9	<0.9	<0.8
	Community involvement	High	Low	None
	Artisanal fishing (OHI)	High access	Low access to fishing	Very low access to fishing
	Vital protein source	Low	Medium	High
Variable 4—Industry				
Small-scale fisheries employ more than 90% of the world's 36 million fishers (FAO, 2016). The annual value of fish products is estimated to about $U.S.94 billion (FAO, 2016). However, a study by the World Bank and FAO (2008) showed that the	Subsidies(case by case evaluation)	Positive for regulated countries	–	Negative for unregulated fisheries
	Commercial value	Low risk of IUU fishing	Medium risk of IUU fishing	

Continued

Table 1. continued

	Criteria	Score 2	Score 1	Score 0
world's fishing fleets have an annual economic loss of some U.S.$50 billion, calculated as the difference between the potential and the actual net economic benefits due to government subsidies and over-exploited fish stocks (FAO and Worldbank, 2008).There are many examples of how fisheries operators influence conservation in a positive way (Brewer and Moon, 2015).				High risk of IUU fishing
	Paid quota or membership fee	Yes, low fee	–	No/no info found
Variable 5—Governance				
The type of governance, including corruption and state legitimacy, plays a vital role on how effective management and conservation measures will be to sustain, in this case, a natural resource such as fisheries (Provan and Kenis, 2007).	Global Peace Index (GPI)	High peace (light yellow)	Medium peace (yellow/orange)	Low peace (red/yellow/brown)
	Gini Index	High equality	Medium inequality	High inequality
	Fragile State Index	Sustainable	Stable	Alert/warning
	Anticorruption Perceptions Index(where more than one country was involved in management, the average score was used)	Low corruption (yellow)	Medium corruption (orange)	High corruption (red)
	State legitimacy	Good (<1.7)	Weak (1.8–4.9)	Poor (>5)
Variable 6—Management				
Managing cumulative anthropogenic pressures on marine ecosystems is a challenge (Halpern *et al.*, 2008b). Given that there are many environmental, biological and socioeconomic variables affecting the overall health of the oceans, decision makers have frequently been asking if there is enough scientific information and knowledge of ecological functions and processes to implement an ecosystem approach to marine and fisheries management (Lester *et al.*, 2010). Ecosystem-based fisheries management include a range of tools, including marine protected areas, ITQs and co-management (Smith *et al.*, 2007; Marshall *et al.*, 2018). However, without appropriate knowledge and understanding of how to design multispecies and multiannual fishing plans and how ecosystems supporting fisheries and the communities the fisheries are imbedded in, it is unlikely that management will succeed. Even though there are many ecological processes to understand further, it is widely recognized that we do have a significant amount of scientific information to start implementing ecosystem-based management all around the world (Tallis *et al.*, 2010; McLeod *et al.*, 2011).	Fisheries legal framework	Yes	Some	No
	Management agency	Yes	–	No
	Overall food provision	Sustainable (>80)	Overexploited/rebuilding (21–79)	High risk of collapsing (<20) or no info
	Life history known	High knowledge	Low knowledge	No knowledge
	Stakeholder involvement	Yes	Little	No
	Stock quota	Yes	–	No
	Property rights	Yes	Partly	No
	Catch/gear restrictions	Yes	–	No
	Seasonal closures	Yes	Planned	No
	Spatial management	Yes	In the process	No/no info
	Monitoring compliance system	Yes	Some, in the process	No plan/programme/info
	Certification	MSC/MBA cert	Other certification	No certification
	Science-based decision making	Yes	Mentions it/somewhat	No
	Food web knowledge	Yes	Some	No
	Breeding/size protection	Protection (area or spp)	Some protection	No protection
	Capacity building	Yes	Little	No info
	By-catch/mortality management (incl. IUU fishing)	Management in place / part of quota	Some	No
	Stock assessments	Population dynamics model	Catch rate vs. historical model	None
	Stock survey	Scientifically collected	Catch base	No survey
	EBFM	Yes	–	No
	Vessel monitoring system	Yes	Some	No

score of 5 in this final rescaling, the variable had to score at the maximum level for all criteria during the initial scoring (i.e. each criterion had to receive a 2 in the initial impact ranking). The aggregate scores for the variables were summed to give an overall score per fishery. There was no differential weighting across the variables.

We acknowledge that bias may be introduced by having a different number of criteria per variable and by applying equal weighting across all variables. Given the available data such an approach is valid, robust, and defensible.

Due to the challenges associated with drawing together such broad ranging information, a case-study approach was used for this investigation so that concepts might be developed and generalizations identified from which could be developed a framework for future broader application (Evans, 2002; Dixon-Woods *et al.*, 2005; Jabareen, 2009). Thirty-two fisheries world-wide were investigated initially, and 21 of those were judged to have sufficient data available for our analysis while also representing a diverse set of fisheries types. The fisheries chosen represent pelagic, demersal, and crustacean fisheries; are managed by developing and developed countries as well as by regional fisheries management organizations of the high seas; are a mix of deep sea and shallow sea fisheries; and represent sustainable, depleted, and collapsed fisheries (at the time of data collection, 15 fisheries were categorized as sustainable, 1 was depleted and 5 were collapsed). Where multiple stocks are considered within one fishery (e.g. each of the cod fisheries listed is considered to have multiple constituent stocks), the fishery was classified based on the status of the majority of stocks. While at least 1 of the 5 orange roughy stocks recognized in Australia was not considered as heavily depleted, the majority of the entire fishery was classified as collapsed. These fisheries-level classifications were checked with experts on each fishery (as detailed further below).

Methods and results

Methods

Multivariate analyses were used to identify similarities and differences among the different fishery sustainability categories and, in particular, to identify those variables that most clearly differentiate among fisheries classified as sustainable, depleted, or collapsed. We compared results of multidimensional scaling (MDS) (Young, 2013), an unconstrained ordination, and a canonical analysis of principal (CAP) coordinates (Anderson and Willis, 2003), an ordination constrained by the *a priori* classification of fisheries as sustainable, depleted, or collapsed. MDS, CAP, and radar charts were used to display groupings and ratings among the fisheries, variables, and criteria. MDS and CAP were undertaken using the PRIMER6 package with the PERMANOVA+ add-on (Anderson *et al.*, 2008). It is useful to compare MDS and CAP ordinations of the same data since the degree of (dis)similarity in the two ordinations provides useful information of the relative magnitude of within- and between-group variability, i.e. it is more informative to run both analyses than either one on their own.

Analysis included investigating all variables, all criteria, and all fisheries simultaneously, and then looking at each of the variables and their associated criteria separately. The radar charts showed the individual score per variable, and a holistic overview of the contributions across the six different variables per fishery.

Results

The three categories of fisheries (sustainable, depleted, and collapsed) were all found to have scores for individual criteria that ranged from low to high (Table 2), i.e. no fishery demonstrated uniformly high or low scores across all variables. For example, the sustainable Peruvian anchoveta fishery had the highest score for "biology" (5), but a low score for "environment" (2.2), and a very low score for "governance" (0.5). The collapsed orange roughy stocks in Australia had the lowest "biology" score (2.5), but a high "management" score (4.5). For the total score (a maximum possible of 30), the sustainable Australian Northern prawn and WA rock lobster fisheries scored the highest (25.1 and 24.7), while the collapsed EU eel fishery and depleted Patagonian toothfish in South Africa scored the lowest (15.1 and 15.2).

There was no difference between developing and developed countries with regards to the presence of sustainable vs. depleted/collapsed fisheries, suggesting that for long-term commercial fisheries, there are criteria other than governance alone that influence the sustainability of fished stocks. The three fisheries that received the lowest scores (South African Patagonian toothfish, EU eel, and Namibian sardines) were defined as collapsed or depleted. However, the absolute score is not a reliable indicator of fishery sustainability by itself, as a number of "sustainable" fisheries had a relatively low overall score.

All the depleted and collapsed fisheries were associated with a medium to high risk of IUU fishing, while for sustainable fisheries the risk of IUU was low to medium. A high score (i.e. 2 in the initial scoring) for the anti-corruption criteria meant that the government structure and management is perceived as open and transparent, which may help combat IUU fishing and corruption. While a high score (2) for this anti-corruption criterion is not a guarantee of no corruption, it does indicate the existence of regulatory measures that make it more difficult to perform illegal or unethical actions.

Multivariate analyses

While the MDS did produce a tight cluster of fisheries (in which the majority but not all were those classed sustainable), with a halo of other fisheries, there was no simple pattern based on taxa, fishery status, or geographic region. While some claim can be made that Southern hemisphere stocks (anchoveta, seabob, southern bluefin tuna, hake, and some toothfish) sit separate to northern stocks, this is not true for all as the orange roughy, northern prawn, and some of the toothfish fisheries sit in amongst the tightly clustered group (Figure 1, bottom left). Similarly, while there appears to be some separation between toothfish and forage fish (sardine, hake, and anchoveta) fisheries, again the demarcation is not unequivocal as herring and other toothfish again sit in the tight central clump (Figure 1). Likewise, while the majority of the tightly clustered fisheries (Figure 1, bottom left) are marked as sustainable (Alaska Pollock, cod EU, cod Iceland, cod Norway/Russia, herring, Northern Prawn Fishery, Australian toothfish, South Georgia toothfish, rock lobster WA), two are collapsed (cod in Canada, orange roughy). The tight cluster represents fisheries with high aggregate scores for the 21 management criteria (Figures 1, 3a, d, i, j, l, and m, 4b and e). The collapsed eel and southern bluefin tuna fisheries stand out from all others, with a low overall score, particularly for industry, governance, and management (Figures 1 and 5c and d).

Table 2. Assessment of fisheries indicated by the aggregate scores for each of the six variables (B, biology; E, environment; SE, socioeconomic; I, industry; G, governance; M, management).

	Scale: 1–5 (1 = poor, 5 = excellent)						
Fisheries	**B**	**E**	**SE**	**I**	**G**	**M**	**Total**
Northern Prawn Fishery (*Fenneropenaeus merguiensis, Fenneropenaeus indicus, Penaeus esculentus, Penaeus semisulcatus, Metapenaeus endeavouri, Metapenaeus ensis*), sustainable (Northern Australia)	4.6	4.1	3.9	4.2	3.5	4.8	25.1
Rock lobster (*Panulirus cygnus*), sustainable[a] (Western Australia)	4.6	3.4	3.6	5.0	3.5	4.6	24.7
Herring (*Clupea harengus*), sustainable (Iceland)	3.9	4.1	3.6	5.0	3.0	4.8	24.3
Patagonian toothfish (*Dissostichus eleginoides*), sustainable (Macquarie Island, Australia)	4.6	4.1	2.9	4.2	3.5	4.9	24.1
Rock lobster (*Jasus edwardsii*), sustainable (Tasmania, Australia)	4.6	3.1	4.3	4.2	3.5	4.0	23.7
Cod (*Gadus morhua*), collapsed (Atlantic Ocean, Canada)	3.6	3.1	4.6	3.3	4.0	4.6	23.3
Cod (*Gadus morhua*), sustainable (Iceland)	3.9	3.1	3.6	4.2	3.5	4.6	22.9
Cod (*Gadus morhua*), sustainable (Barents Sea, Norway/Russia)	3.9	3.1	4.3	4.2	2.0	5.0	22.5
Alaska Pollock (*Gadus chalcogrammus*), sustainable (Alaska, USA)	4.3	3.8	3.6	4.2	2.0	4.5	22.3
Cod (*Gadus morhua*), sustainable (EU, Baltic Sea)[b]	3.9	3.4	3.6	1.7	4.5	4.5	21.6
Patagonian toothfish (*Dissostichus eleginoides*), sustainable (South Georgia Islands, UK)	3.9	2.8	1.8	4.2	4.0	4.8	21.5
Orange Roughy (*Hoplostethus atlanticus*), collapsed (Tasmania, Australia)	2.5	3.8	3.6	3.3	3.5	4.5	21.2
Southern Bluefin Tuna (*Thunnus maccoyii*), collapsed (CCSBT, high seas)	3.6	3.1	3.6	2.5	3.0	3.7	19.5
Hake (*Merluccius paradoxus*), sustainable (South Africa)	3.2	3.8	1.8	5.0	1.0	4.2	18.9
Anchoveta (*Engraulis ringens*), sustainable (Peru)	5.0	2.2	2.1	4.2	0.5	3.7	17.7
Hake (*Merluccius gayi peruanus*), sustainable (Peru)	3.9	2.5	2.5	4.2	0.5	3.8	17.4
Antarctic and Patagonian Toothfish (*Dissostichus mawsoni and Dissostichus eleginoides*), sustainable (CCAMLR, Ross Sea, high seas)	3.9	4.4	1.4	3.3	0.0	4.0	17.1
Atlantic seabob (*Xiphopenaeus kroyeri*), sustainable (Suriname)	3.6	3.4	2.1	3.3	0.5	4.2	17.1
Sardines (*Sardinops sagax*), collapsed (Namibia)	3.2	2.2	1.8	3.3	1.5	4.0	16.1
Patagonian toothfish (*Dissostichus eleginoides*), depleted (Prince Edward Island, South Africa)	3.6	3.8	0.0	3.3	0.5	4.0	15.2
Eel (*Anguilla anguilla*), collapsed (EU, high seas)	2.9	3.1	2.5	1.7	2.5	2.5	15.1

The maximum possible score for each variable was 5 (indicating desirable attributes) and thus the maximum possible overall score per fishery was 30. The fisheries are presented from highest to lowest total score. High scores indicate features deemed "positive" for the fishery, while low scores indicate a "negative" attribute.

[a]This stock is considered sustainable despite an extended period of low puerulus settlement, as this climate-driven phenomenon was compensated for by significant effort reductions designed to increase residual stock abundance (de Lestang *et al.*, 2014).

[b]At the time of data collection, the Baltic cod fishery was MSC certified, and based on the overall information available at the time it was classed as a sustainable fishery. In December 2015, however, the fishery lost its MSC certification. As stock assessment data are uncertain, it may now have a different classification.

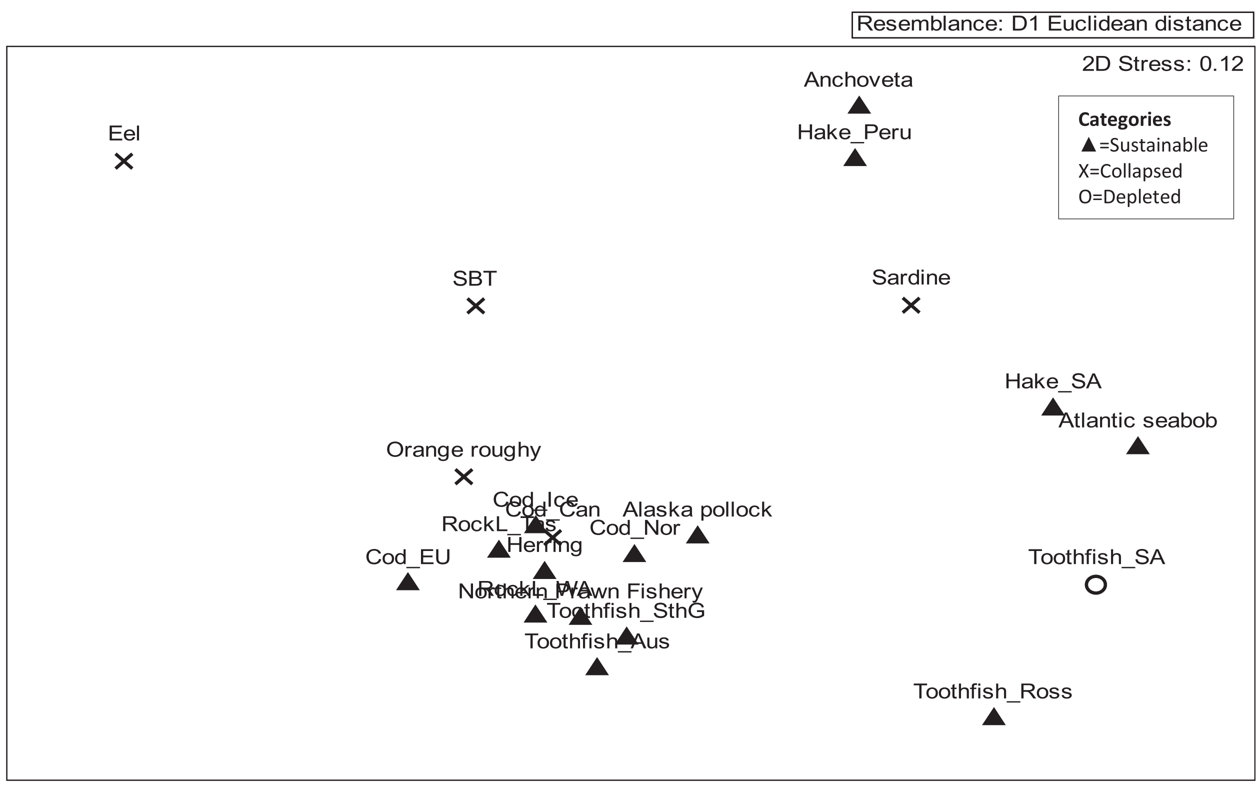

Figure 1. MDS plot indicating the target taxa and status of the different fisheries (S, sustainable; C, collapsed; D, depleted).

In contrast, the CAP analysis showed a clear separation of stock categories, particularly of collapsed/depleted vs. sustainable fisheries (Figure 2). The distinct differences in the two ordinations of the same dataset indicates that that variation across characteristics of fisheries within a stock status category is large relative to differences in the characteristics of the fisheries between the different stock sustainability categories. Thus, in the unconstrained MDS ordination, separation of fisheries only weakly aligns with stock status (Figure 1). In contrast, when fishery status categories are defined and the CAP ordination constrained accordingly (i.e. to maximally differentiate between status categories relative to variation within categories), the different stock categories become more distinct, particularly in the separation of collapsed/depleted fisheries from sustainable fisheries (Figure 2). Thus, the vector overlay enables unambiguous identification of the criteria that best align with the distinction between collapsed/depleted and sustainable fisheries.

For the CAP analysis, the first two canonical correlations are $\delta_1 = 0.91$ and $\delta_2 = 0.55$, indicating clearly that CAP1 is most strongly associated with group differences, consistent with the ordination which shows clear separation of "sustainable" and "collapsed" stock on the first CAP axis (Figure 2). By considering the vector overlay associated with the CAP analysis, it is possible to identify the key criteria that best discriminate between sustainable and unsustainable fisheries (at least in terms of realized stock status), namely disease, closures, certificate, Age_Size, and Comm_Value. This means that sustainable fisheries had certification, a commercial value that prompted efforts in management, little or no disease present, management tools in place (such as MPAs or seasonal closures, TAC, and size and gear restrictions), and they had a size/age distribution amenable to sustaining a future stock. Increasing values of all these criteria align with the sustainable fisheries.

Sustainable fisheries

For the sustainable fisheries, the overall score ranged between 25.1 and 17.1. The 15 sustainable stocks had an average score of 4.1 for biology, 3.4 for environment, 3.0 for socioeconomic, 4.1 for industry, 2.4 for governance, and 4.4 for management. All sustainable fisheries scored above 4 on biology, management, and industry criteria. This means that the sustainable fisheries scored highly with regards to the several criteria associated with each of these three variables. For example, all sustainable fisheries scored 2 (out of a maximum possible 2) for information on viable age/size distribution (making it possible to sustain the stock), while none of the collapsed/depleted fisheries did.

The fishery that reached the highest overall score was the Australian Northern Prawn Fishery (total score = 25.1). It scored very highly on biology, environment, industry and management, and high on socioeconomic criteria (Figure 3l). The WA rock lobster had the second highest score (total score was 24, 7) (Figure 3b). Iceland also manages a sustainable cod fishery, which had high scores for industry and management criteria with an overall score of 24.3 (Figure 3g). Equally high was the sustainable cod fishery in the Barents Sea, jointly managed by Norway and Russia, with high scores for industry, socioeconomic and management criteria, and with an overall score of 23.0 (Figure 3i). The cod fishery in the Baltic Sea (at the time assessed as sustainable by MSC) had an overall score of 21.4 (Figure 3m). In December 2015, however, the Baltic cod fishery lost its MSC certification. Although this fishery scored very high for governance and management, it scored low for industry (no paid quota and low commercial value), and attained only moderate scores for environment (very low score on the Ocean Health Index (OHI), high anthropogenic influence on habitat, and high climate variability) and socioeconomic criteria. This fishery would be currently classified as depleted as the stock does not have a viable age/size distribution.

The four toothfish fisheries we analysed are governed by four different nations/organizations, and three of the four were deemed sustainable. Overall, toothfish fisheries separate from the other sustainable fisheries in having high scores for OHI, closure, certification, disease and habitat, and low scores for breeding,

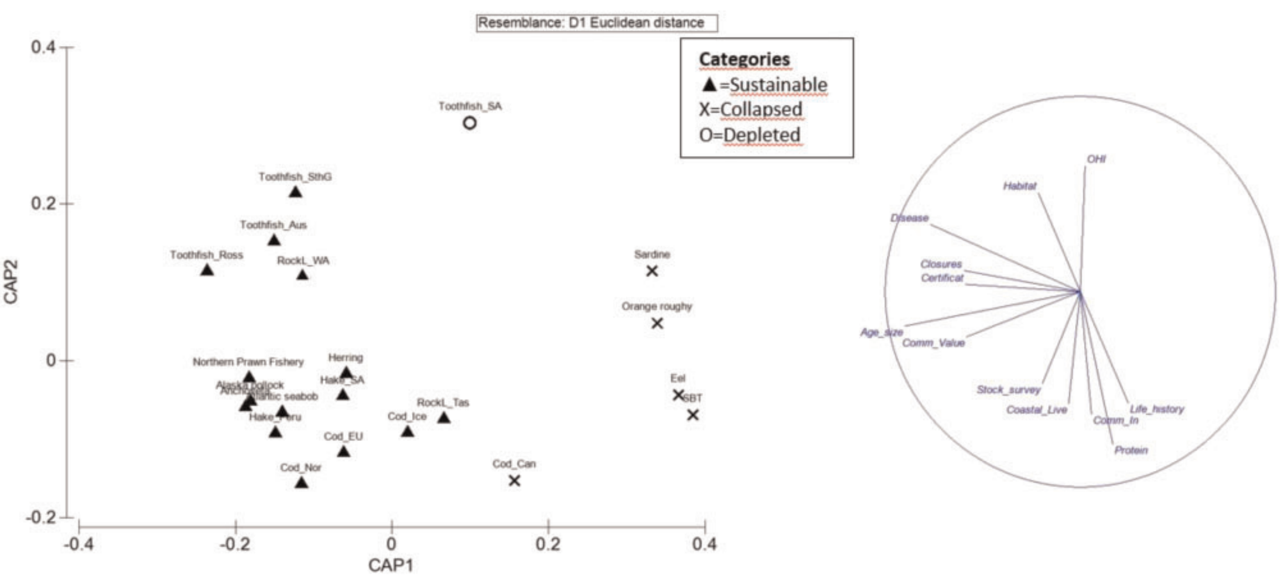

Figure 2. CAP coordinates showing a clear separation between collapsed and sustainable fisheries. The analysis is based on $m = 7$ PCO axes which explained 75.7% of the total variation, and 71.4% of samples were allocated to the correct group (S=sustainable, C=collapsed and D=depleted).

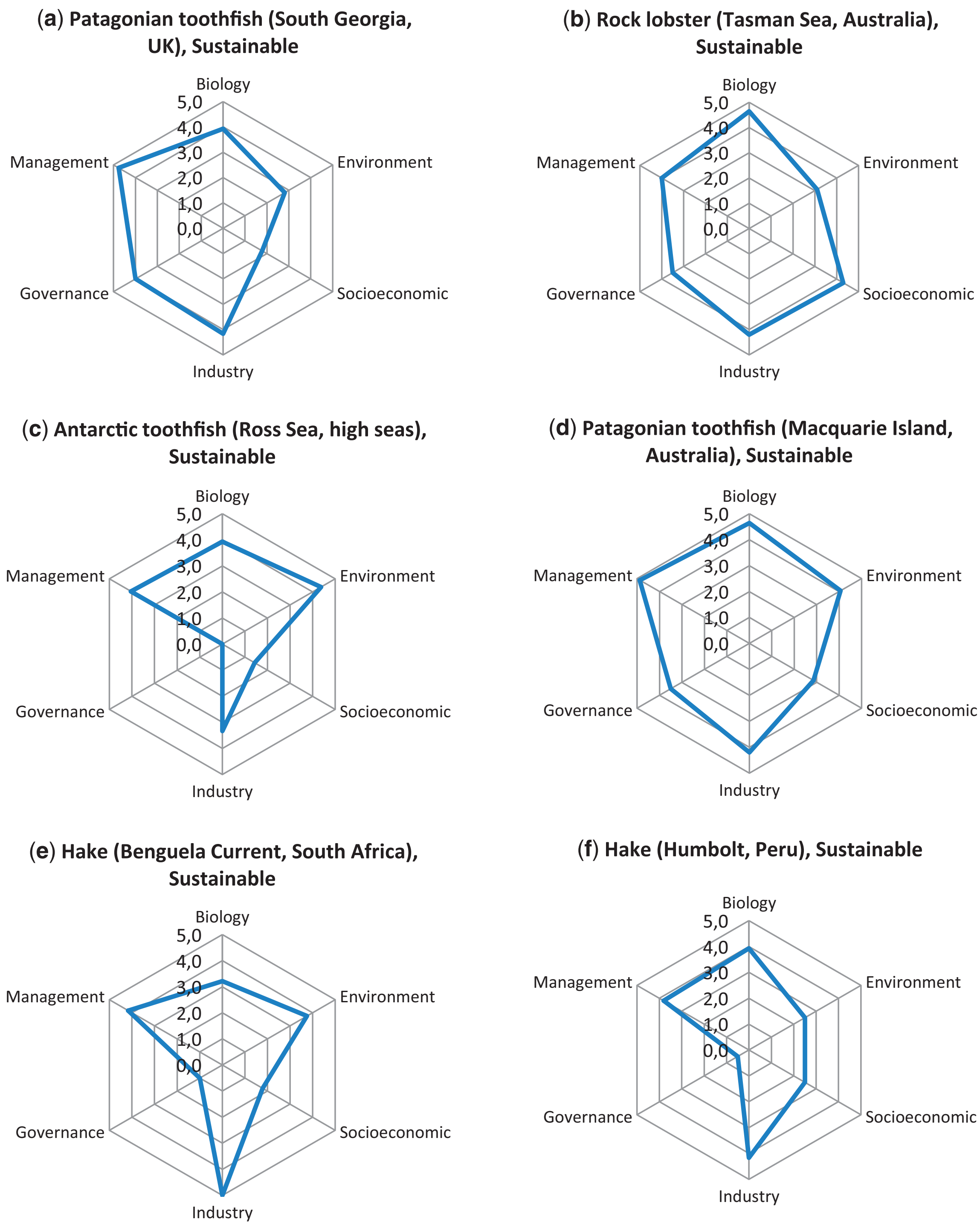

Figure 3. (a–o) Average scores across the six variables for each of the fisheries rated as sustainable at the time of data collection.

stock survey, Gini index, protein source, and community involvement. The depleted South African toothfish fishery differs from the three sustainable ones, mostly with regards to knowledge of stock age and size distribution, commercial value, and to a lesser extent closure and the absence of fishing certification. The sustainable Australian MSC-certified Patagonian toothfish fishery around Macquarie Island scored very highly for biology and management, and high for governance, with an overall score of 24.1 (Figure 3d). The Antarctic toothfish fishery in the Ross Sea, also sustainable, scored high for environment and management criteria but had an overall score of only 17.1 reflecting a low score for governance (Figure 3c), as did the depleted fishery managed by South Africa (Figure 4f). The British Patagonian toothfish fishery around South Georgia scored very high for management, governance, and industry criteria with an overall score was 21.5 (Figure 3a). The risk of corruption, and thereby not complying with the conservation measures in place, seems to be the factor separating these four fisheries.

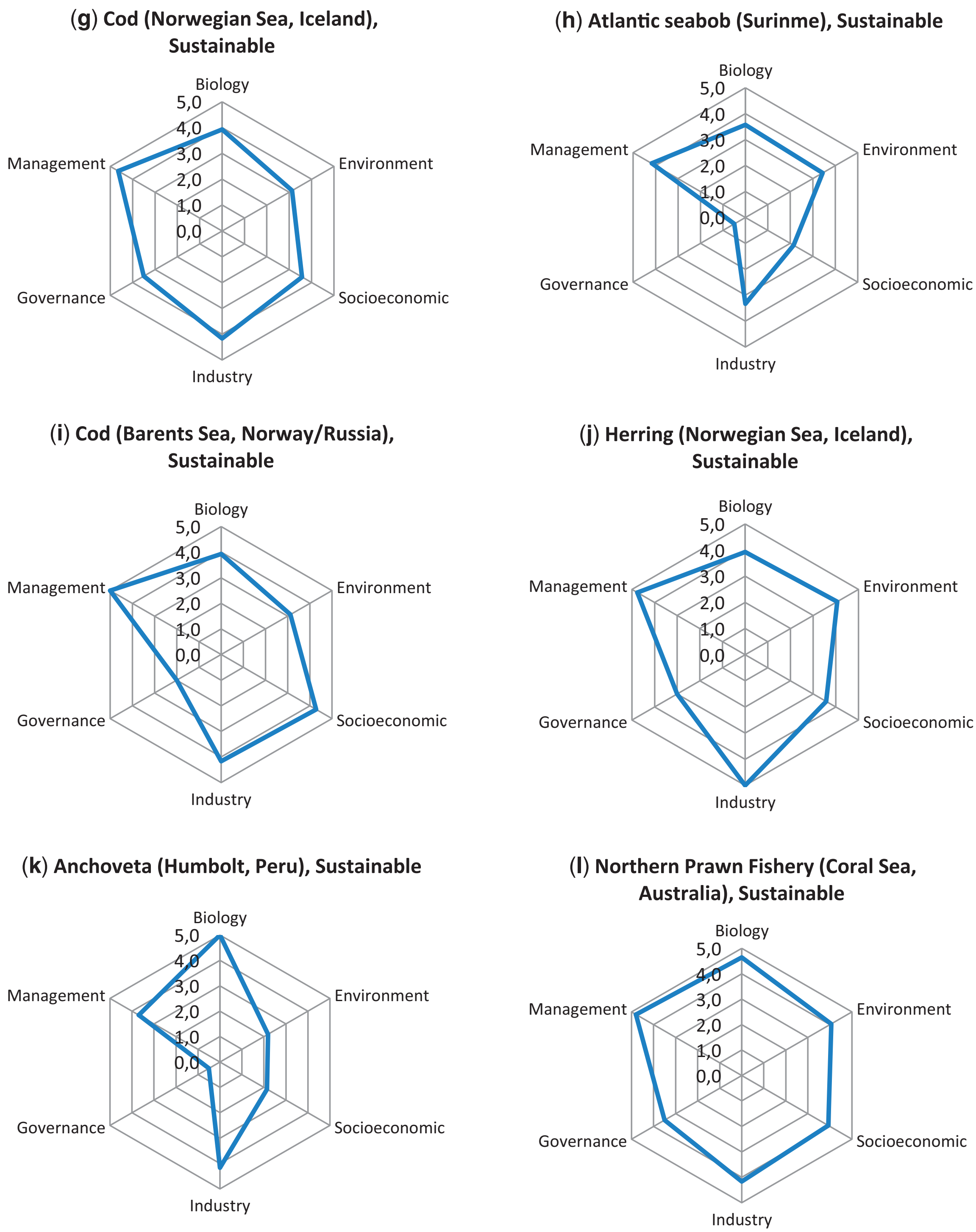

Figure 3. Continued.

Among the sustainable fisheries, scores varied widely for the governance criteria, ranging from 4.5 for the Baltic cod to 0.5 for the hake and anchoveta fisheries in Peru. The sustainable fisheries also demonstrated a large range of scores on social and economic criteria, with the cod fishery in the Barents Sea and the rock lobster fishery in Tasmania scoring the highest (4.3) and the Antarctic and Patagonian toothfish fisheries in the Ross Sea scoring the lowest (1.4). While the sustainable Tasmanian rock lobster fishery and the sustainable Barents Sea cod fishery both scored very highly (4.3) on social and economic criteria, so did the collapsed Canadian cod fishery (4.6). The Western Australian rock lobster fishery had the second highest score of all fisheries surveyed (24.7), with particularly high scores for biology (4.6), industry (5.0), and management (4.6) (Figure 3o).

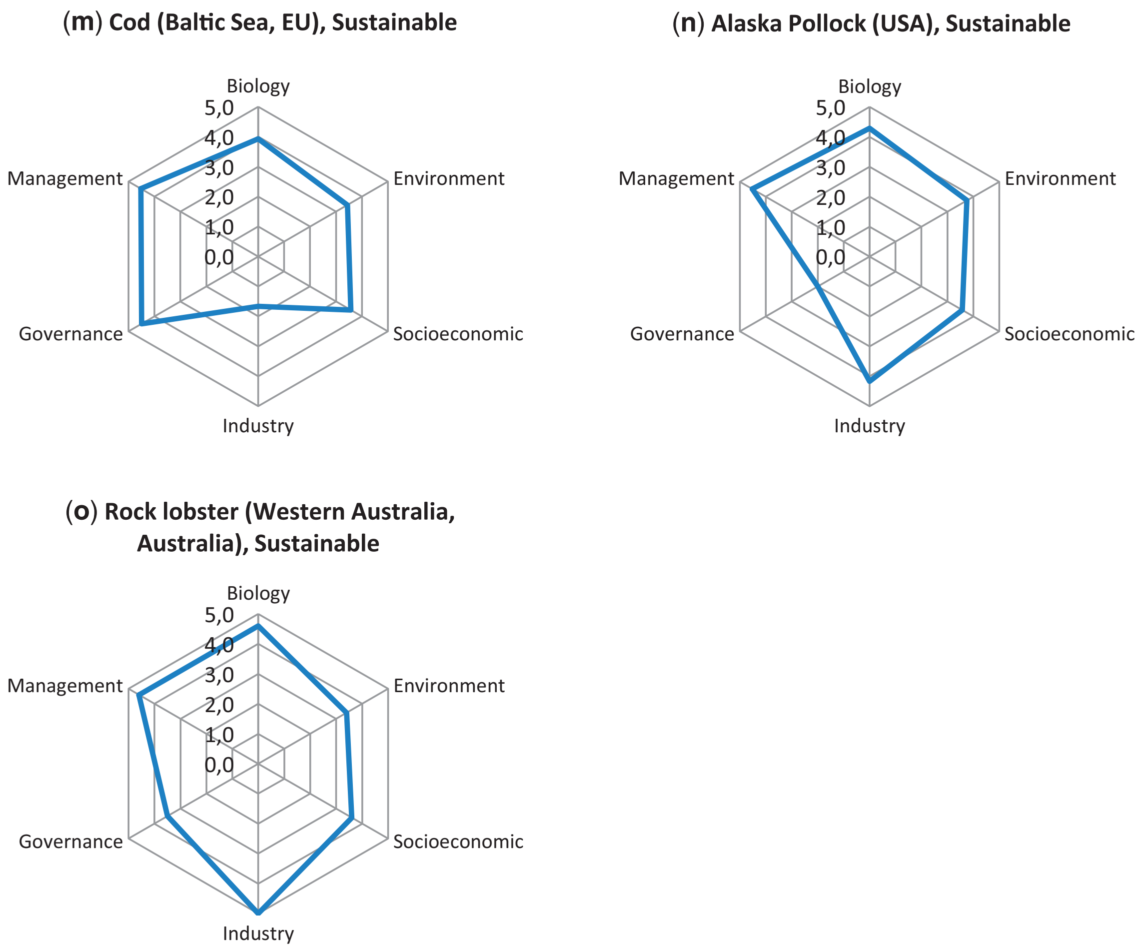

Figure 3. Continued.

Depleted and collapsed fisheries

Total scores for the six depleted/collapsed fisheries also spanned a wide range, between 23.3 (Newfoundland cod fishery) and 15.1 for the collapsed EU eel fishery. The collapsed and depleted fisheries had an average score of 3.2 for biology and environment, 2.7 for socioeconomic, 2.7 for industry, 2.9 for governance, and 3.9 for management—lower scores overall in all of these areas than for the sustainable fisheries (Figure 4a–f).

All but one (orange roughy) of the collapsed fisheries are for migratory species, as well as also having specific habitat specializations. Also, all but one of the collapsed fisheries are slow breeders. All collapsed fisheries apart from orange roughy were challenged by disease, and their high economic value was considered a negative impact on the stock (i.e. motivating IUU fishing). The depleted South African toothfish scored high for biology, environment, and management but very low for socioeconomic and governance criteria (Figure 4f). The eel fishery was the epitome of the scores for the collapsed fisheries, scoring low for all the six variables (Figure 4d), while the cod fishery in Canada was distinctly different from the others—with medium, high, or very high scores on all variables (Figure 4e).

Almost all of the 15 sustainable fisheries got high scores for all the six variables, whilst the collapsed/depleted ones had a wider variability of scores among the variables (Figure 5a).

Based on mean values, the major differences between sustainable versus collapsed/depleted fisheries for the six variables were biology, environment, and industry (Figure 5b).

Discussion

Our analysis showed a clear separation between collapsed/depleted and sustainable fisheries, although there were differences within a stock status category (Figure 2). We also discovered that sustainable fisheries (Alaska Pollock, cod EU, cod Iceland, cod Norway/Russia, herring, Northern Prawn Fishery, Australian toothfish, South Georgia toothfish, and rock lobster WA), and collapsed fisheries (cod in Canada, orange roughy) could score highly on management criteria, suggesting either that characteristics of management alone are insufficient to determine stock status, that management responses in the collapsed/depleted fisheries had been invoked too recently to have yet had much effect on the stock, or that management gets it wrong. Seven of the nine fisheries with high management scores had a paid quota system. The collapsed eel and southern bluefin tuna fisheries, both exposed to IUU fishing particularly in the high seas, had a low overall score, specifically for industry, governance, and management. All but one of the depleted and collapsed fisheries scored very highly on management, confirming that sustaining and

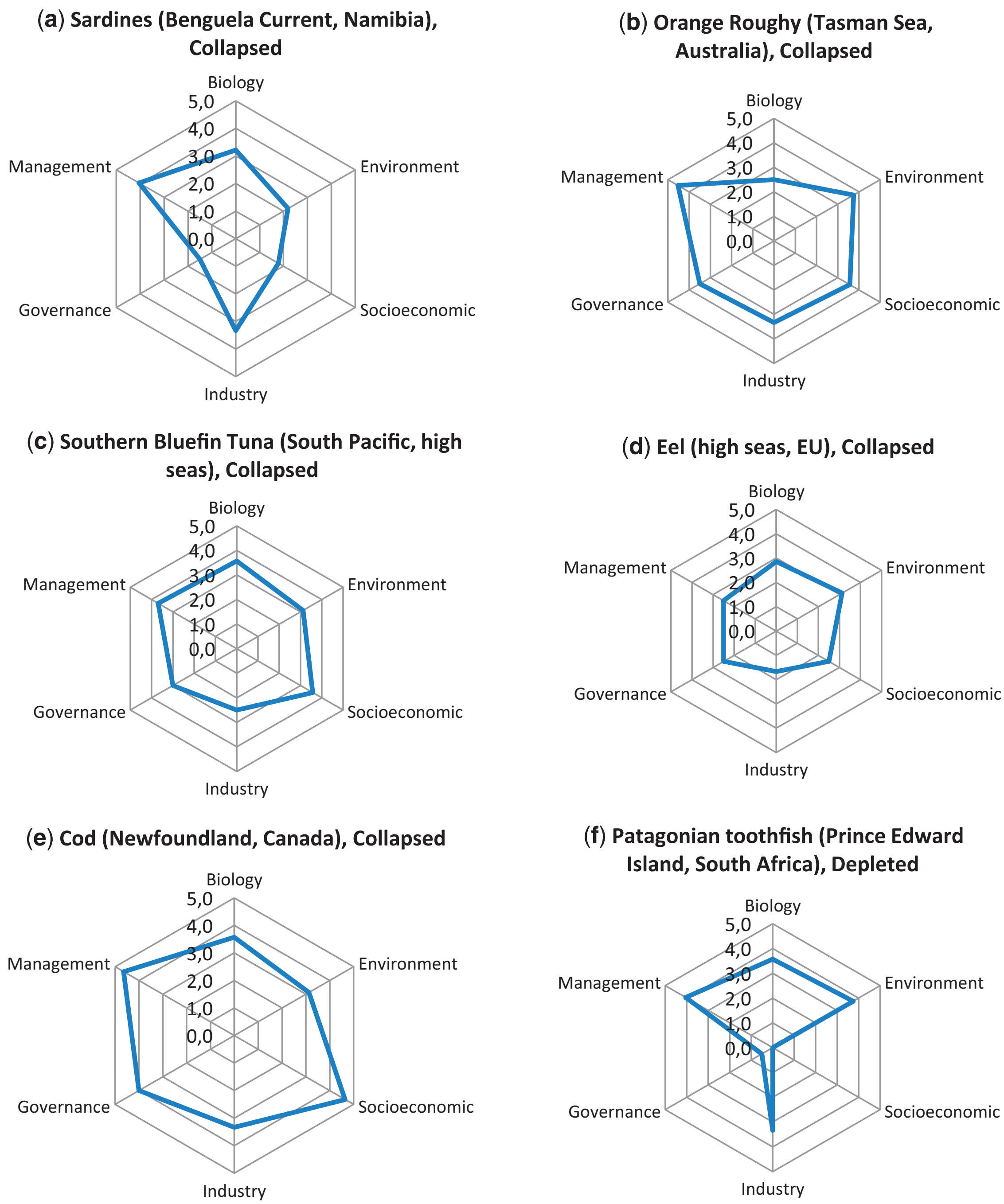

Figure 4. (a–f) The average scores for the six variables for the collapsed and depleted fisheries.

recovering fish stocks is a challenging task (Hilborn and Walters, 2013).

Of the 21 fisheries analysed almost all of the 15 sustainable ones got high scores for all the six variables, whilst the collapsed/depleted fisheries had a wider variability of scores among the variables. When faced with the challenges of marine resource management, both managers and other stakeholders need to identify the conditions that contribute to sustainable fisheries. Is the Australian Northern Prawn Fishery sustainable because biological traits are very well known? Is it sustainable because management works closely with researchers and industry? Is it sustainable because there is an effort control system in place, controlling over-capacity? Is it because the fishery has moved to an MEY target reference point, which is more conservative than an MSY target point (potentially making the fisheries more resilient)? In all likelihood it is a mix of all.

Our analysis showed that within the three groups of fisheries (sustainable, depleted, and collapsed), the overall scores had a wide range, revealing wide variability in the capacity and process of fisheries management, and emphasizing that high performance over a range of highly diverse variables are necessary to guarantee that a fishery has a high likelihood of sustainability. Equally, no

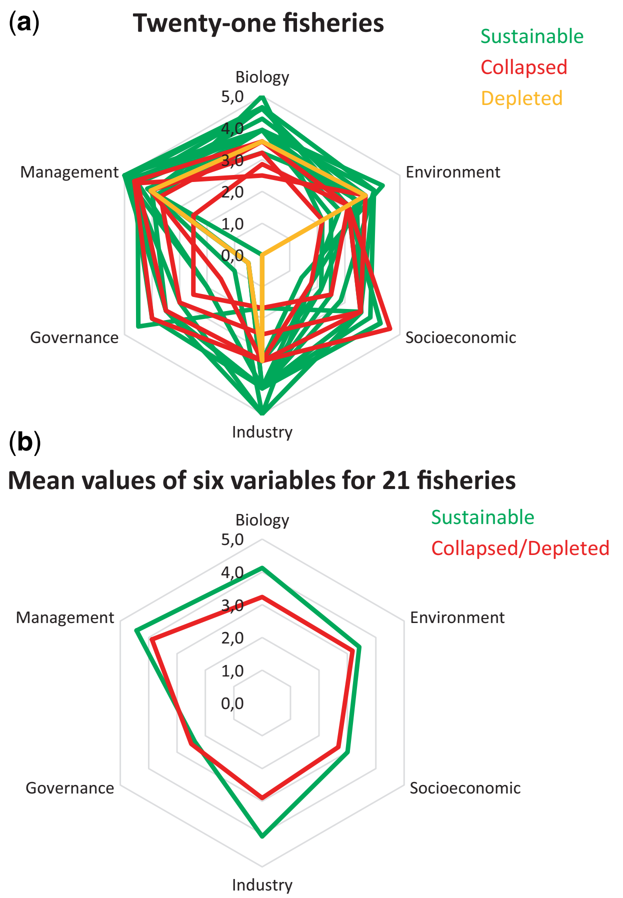

Figure 5. (a) The sustainable fisheries mostly ranked high on all the six variables. (b) Mean values of the six variables for the 15 sustainable and the 6 collapsed/depleted fisheries.

single variable or criterion marks a fishery as prone to collapse. Rather it is the combination of a set of factors involving biological and environmental knowledge, governance and management impacts, socioeconomic and industry parameters. Even when a wide selection of management tools, including effort and harvest controls are in place, together with social and economic considerations are in place, a stock may still collapse (due, for example, to a lack of stock data on growth and recruitment rates, or data on age at maturity), as has occurred spectacularly in both the cod fishery in eastern Canada and the orange roughy in Australia. At the other end of the spectrum, fisheries that might not have the same degree of management measures in place, such as the Peruvian anchoveta, may remain robust due to their biological responsiveness to relatively quickly recover from decreases in biomass if no other stressors are present.

We found that across the 21 fisheries considered, there was typically good biological knowledge of the fished stocks, a wide range of management tools (legal framework, management agency, use of TACs, catch and gear restrictions, stock assessment, and spatial management), and industry incentives (in particular a paid quota system) were present in some form. This does not mean all fisheries were similar and while all 21 fisheries have a legal framework and a marine management agency in place, it was not possible to investigate how effective compliance with the frameworks was. In addition, all but one of the collapsed/depleted fisheries have high scores for management criteria, which could be a direct result of initiating additional management actions in response to the collapse (or in an effort to avert it). It could also be that it takes time to fully implement management tools and for an increase in stock abundance to occur.

Not surprisingly, all but one of the sustainable fisheries investigated had a viable size/age distribution, while none of the collapsed ones and the depleted one had not. The single exception, was the WA rock lobster which was coming off an extended period of poor recruitment due to climate drivers (de Lestang *et al.*, 2015).

Interestingly, the collapsed fisheries all had a medium–high risk of IUU fishing, while all the sustainable fisheries had a low–medium risk. This supports the idea that (i) high valued species are prone to IUU fishing, (ii) but with appropriate measures the risk of IUU may be reduced, and that (iii) high presence or risk of IUU and corruption is a clear marker of a fishery in trouble (as it does not have the will or capacity to enforce regulations) (Schmidt, 2005; Le Gallic and Cox, 2006).

Biology and environment

Biology was one variable that showed high scores for all of the sustainable fisheries. This is not surprising, as fundamental knowledge about a species biology and the environment in which it lives is essential for identifying the appropriate management tools that are needed to obtain sustainable fish stocks in the long term (King, 2013). It is clearly important that a stock has a viable size and age distribution that can support exploitation and rapidly recover from overshoots or stochastic events that may exacerbate downturns (Enberg *et al.*, 2009). Here the analysis showed that all but two of the collapsed and depleted fisheries are slow breeders, suggesting that it is harder to manage or recover species that mature late (Heppell *et al.*, 2005). This research further supports the finding that maintaining a viable age/size distribution is essential for long-term sustainable fish stocks (Berkeley *et al.*, 2004; Hilborn and Walters, 2013).

Ongoing monitoring of environmental variables in the context of fisheries is clearly important in managing for sustainability. For example, the rock lobster in Western Australia has one of the world's longest time-series of abundance estimates, and it is generally considered that appropriate conservation measures were in place (Penn *et al.*, 2015) including precautionary fishery adjustments based on responses to observed levels of recruitment (puerulus settlement) (de Lestang *et al.*, 2015). Additional significant changes occurred in this fishery following a marine heat wave (Pearce *et al.*, 2011) and this flags that even if a species has been sustainable in the past it might not be under environmentally altered conditions—or at least they may not be sustainably exploited to the same levels as in the past.

Social and economic conditions

The collapsed Canadian cod fishery had the highest socioeconomic rating of all the 21 fisheries investigated, suggesting that the considerable management resources available was due to the fact that the fishery was recognized as vital for sustaining fisheries-dependent communities in Newfoundland and Labrador (Bavington, 2011). This could also have put pressure on politicians to permit ongoing fishing since fishing was the main industry sustaining these communities. While the rock lobster fishery in Tasmania also had a high socioeconomic score (4.3), its sustainability may reflect the smaller size of fishing-dependent communities and the close collaboration between the government, industry, and independent researchers (Johnson *et al.*, 2013; Marzloff *et al.*, 2016a). However, it is worth noting that since the time of our analysis, an increase in the frequency of extreme climate events around Tasmania has put into question the status of this stock (Marzloff *et al.*, 2016b).

Management and governance

Governance in this analysis showed both high and low scores within all three categories of fisheries. The seabob fishery in Suriname is MSC certified, showing that an external validation system can help overcome issues associated with corruption and management to achieve a sustainable fishery. However, there is no guarantee that MSC-certified fisheries in developed nations with low corruption will remain sustainable, as exemplified by the Eastern Baltic cod managed by the EU, which lost its MSC certification in 2015 (MSC, 2015) after the analysis we present here was completed. Given the variability in environmental factors, such as oxygen and salinity, in this area that affect cod survival rates (Köster *et al.*, 2005), and the challenge with overfishing and potential collapse that already existed prior to the MSC certification (Lindegren *et al.*, 2009), it is not surprising that this fishery is no longer classified as sustainable.

The fisheries studied here are long-term commercial fisheries with a large range of management tools in place. The fact that all fisheries considered in this analysis scored high for most of the management criteria may simply reflect that only commercially highly valuable stocks (which tend to attract management efforts) had sufficient data available to be included in the analysis. That more than 80% of the world's catch lacks adequate stock assessment should clearly be cause for significant concern (Costello *et al.*, 2012, 2016). The main reason for this may be that both data availability and assessments are limited in some parts of the world, but despite these data poor fisheries, about 33% of the world's fisheries were classified as overfished in 2015 (FAO, 2016, #550).

Differential success in the implementation of management of the surveyed fisheries, including monitoring and adaption, is reflected in that some stocks are depleted or collapsed despite application of many of the recommended "best practice" management tools. In addition, current management methods may be in place in an effort to avert collapse or recover from it. The Atlantic cod fishery of Newfoundland and Labrador is often used as an example for mismanagement leading to collapse (Milich, 1999). Our analysis showed that although the fishery scored highly on management, governance, and socioeconomic criteria, the stock did not have a viable age/size distribution. This was possibly due to the fact that the annual survival probabilities had a twofold decline in the 1980s, which occurred at the same time as declining catch rates, and increased effort in both in- and offshore fishing (Hutchings and Myers, 1994). Even though large resources in terms of governance and management were not able to set a TAC to sustain the fishery and prevent a collapse in the 1990s, the management efforts since are most likely to have contributed to an increase in abundance and size composition some 25 years after the moratorium in 1992 (Rose and Rowe, 2015).

Industry

A majority of the sustainable fisheries (the exceptions being the Northern Prawn Fishery and Antarctic toothfish within the CCAMLR convention area) were based on individual property rights. All the fisheries—except for the collapsed eel fishery and the Baltic cod fishery—had a system where fishers have to pay a fee to fish (including a membership fee paid to a management organization such as CCAMLR). These two findings support other studies of how individual transferable quotas (ITQs) and license fees can be an effective management tool, providing the TAC is sensible, together with other conservation measures, to combat overcapitalization and overfishing (Branch, 2009; Färe *et al.*, 2015).

While there is always a risk of IUU fishing, particularly for high-valued species, an ITQ system might be one tool to also sustain the social and economic goals of fisheries, provided that the available biological information allows for the setting of a sensible TAC (Schaltegger and Wagner, 2017). One example of this is the South African Patagonian toothfish. IUU fishing was first detected in this fishery in 1995, but is believed to have started in 1994, with IUU catches estimated to be higher than the legal catches (Brandão and Butterworth, 2009). Measures implemented to combat the IUU fishing included a paid quota scheme as well as participation in CCAMLR's catch documentation scheme (CDS). Despite these measures, retrieved illegal fishing gear and observed IUU vessels confirms that IUU fishing persists in the area (CCAMLR, 2015). Stock abundance and potential recovery is uncertain, not only because of IUU fishing activities but also because different types of stock abundance measuring methods have been used (CCAMLR, 2015).

The toothfish fisheries

The four toothfish fisheries studied here are underpinned by different management organizations. Three of the fisheries are managed by individual nations (Australia, South Africa, the United Kingdom). In contrast, the Ross Sea toothfish fishery is more at risk because it is a straddling stock, and CCAMLR's member states have mixed anticorruption weightings (3 members are rated as "highly corrupt" and 11 as "moderately corrupt") (Nilsson *et al.*, 2016), which suggests that the behaviours of members and fishers and their willingness to comply with measures and regulations may be variable.

The mostly deep-water Antarctic and Patagonian toothfish have complex life histories including late maturity, high interannual variability in reproductive traits, specific habitat use, and movement over its more than 50 year life span, making them particularly vulnerable to overfishing as any recovery process would be long (Péron *et al.*, 2016). Toothfish, or "white gold", is also a highly valued species making it particularly sensitive to IUU fishing, both by licensed and non-licensed operators. Although a large range of management measures are in place—including total allowable catch (TAC) and vessel monitoring systems, together with a scientific observer programme and a CDS—IUU fishing in the Southern Ocean remains a problem (Miller *et al.*, 2016). Further support for this is a study showing that 76% of fish on a Chinese market was mislabelled to overcome the CDS in place by CCAMLR for Patagonian toothfish (Xiong *et al.*, 2016). Despite Australia and France using armed patrol vessels (in French and Australian territorial waters of the Southern Ocean) IUU fishing of toothfish may be far from being eradicated (Clare, 2010).

The three sustainable toothfish fisheries we analysed showed that the Ross Sea fishery has a low anticorruption index. This may imply that the fishery in the Ross Sea is at risk as there is a high risk for corruption (i.e. IUU fishing). The overall decrease of Patagonian toothfish in the Southern Ocean has occurred because this high-valued species is profitable even when illegally caught (although few sightings have been reported in the last few years), and there is a low risk of being caught (Agnew *et al.*, 2009; Brooks and Ainley, 2017). The Ross Sea toothfish was defined as sustainable, mainly because of the conservation measures in place by CCAMLR, but had a low overall score. Even though the value is high (even on the illegal market), this fishery may remain sustainable due to the 1.55 million km^2 MPA that was implemented in the Ross Sea on 1 December 2017, with a 1.2 million km^2 no-take zone (CCAMLR, 2015).

The toothfish fisheries managed by CCAMLR may be at risk as toothfish matures late, has low fecundity rate, and is slow growing (Collins *et al.*, 2010); CCAMLR has no ITQ system in place; there also is no, or little, control of actual catches (the observers record some scientific data, not actual catches); there is low reporting of by-catch; and there is evidence of IUU (Ainley *et al.*, 2012; Ainley and Pauly, 2014; Xiong *et al.*, 2016).

The cod fisheries

The four cod fisheries we examined are all managed by developed countries. The two sustainable cod fisheries in Iceland and Norway/Russia scored highly on the industry, management, and biology criteria. In addition to the management tools in place for these fisheries, the warming water allowing changes in distribution and higher survival and recruitment levels might also be factors influencing the observed increase in abundance of the two stocks (Budreau and McBean, 2007).

The other two cod fisheries (Canada and Baltic Sea) are collapsed or depleted. Both of these classes of fisheries score high on the governance, management, and biology criteria but they score low on industry, suggesting that economic measures and incentives may be useful in managing effort, as was seen for the sustainable Northern Prawn Fishery.

The Australian fisheries

For the five Australian fisheries analysed here, four are sustainable and one is collapsed. The sustainable MSC-certified Patagonian toothfish in Australia's sub-Antarctic territory scored very high for management, biology, and industry, and the sustainable Northern Prawn Fishery was a standout, scoring very highly for biology, environment, management, industry, and socioeconomic variables.

The collapsed deep-sea orange roughy was closed in 2006 (apart from on the Cascade Plateau) (AFMA, 2014), and this late maturing species (27–32 years of age) has yet to fully recover (AFMA, 2015), although a controlled fishery reopened in Tasmania's east coast in 2015. This emphasizes that even when management is adaptive and enforces a moratorium, recovery and rapid turnaround is not guaranteed—biology will play its part.

The rock lobster fisheries are both sustainable at present, but we note that both are now struggling with direct or indirect impacts related to climate change (Caputi *et al.*, 2010; Johnson *et al.*, 2011; Pecl *et al.*, 2017), highlighting the new suite of challenges facing resource managers even though they are well armed with long-term datasets and relevant management tools.

Developed vs. developing nations

There was no material difference in the performance of fisheries across developed and developing nations for the fisheries considered in this study, suggesting that management and compliance are more important than governance. For example, sustainable fisheries with high or very high scores for management but with very low governance scores were found in the United States, Peru, South Africa, Russia, Suriname, and the high seas. Clearly, it takes more than a high anticorruption index and a transparent governance structure to sustain fish stocks long term.

Conclusion

Sustainable, depleted, and collapsed fisheries are all present in both developed and developing parts of the world. As depleted and collapsed fisheries may not easily recover—causing high biological, economic, and social costs—it is imperative to understand the risk factors so that they can be addressed. The fisheries analysed in this article have all faced changes driven by ecological, economic, and social factors. The analysis of these fisheries shows that priorities for sustaining fisheries include: (i) identifying whether the stock has a viable size/age distribution, as without it stocks risk being depleted no matter what management tools are in place; (ii) the sustainable fisheries showed that ITQs played an important part (given the TAC is estimated appropriately); (iii) developed and developing nations both had sustainable and collapsed fisheries; and (iv) even when a moratorium is in place a stock may recover very slowly as seen with the Canadian cod fishery and the Australian orange roughy fishery.

The analysis showed that all but one of the sustainable, depleted, and collapsed fisheries had very high scores for the 21 management criteria. However, this analysis also showed that although a fishery might have a high score for management, without a medium or high score for biological knowledge, including age/size distribution, sustainability is difficult to achieve. In developing nations with a higher risk of corruption, achieving sustainable fisheries is still possible with sound scientific and management processes and commitments in place, as there is no guarantee that overexploitation will not occur in developed nations with plenty of scientific and management resources deployed. The criteria that overall defined differences between sustainable and collapsed fisheries are, in particular, "age-size", but also commercial value, closures, certification and, to some extent, a lack of disease. The sustainable fisheries all had high scores on biology, management, and industry criteria. None of the collapsed fisheries had a similar pattern of scoring across the six variables, supporting the notion that different fisheries can collapse for different reasons, that managing marine resources is complex, and that an adaptive approach with explicit attention to all of the variables we identified here is essential to maximize the likelihood of achieving sustainable practice in commercial fisheries.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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How to Sustain Fisheries: Expert Knowledge from 34 Nations

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Abstract: Ensuring productive and sustainable fisheries involves understanding the complex interactions between biology, environment, politics, management and governance. Fisheries are faced with a range of challenges, and without robust and careful management in place, levels of anthropogenic disturbance on ecosystems and fisheries are likely to have a continuous negative impact on biodiversity and fish stocks worldwide. Fisheries management agencies, therefore, need to be both efficient and effective in working towards long-term sustainable ecosystems and fisheries, while also being resilient to political and socioeconomic pressures. Marine governance, i.e., the processes of developing and implementing decisions over fisheries, often has to account for socioeconomic issues (such as unemployment and business developments) when they attract political attention and resources. This paper addresses the challenges of (1) identifying the main issues in attempting to ensure the sustainability of fisheries, and (2) how to bridge the gap between scientific knowledge and governance of marine systems. Utilising data gained from a survey of marine experts from 34 nations, we found that the main challenges perceived by fisheries experts were overfishing, habitat destruction, climate change and a lack of political will. Measures suggested to address these challenges did not demand any radical change, but included extant approaches, including ecosystem-based fisheries management with particular attention to closures, gear restrictions, use of individual transferable quotas (ITQs) and improved compliance, monitoring and control.

Keywords: ocean governance; fisheries management; ecosystem-based management; overfishing; sustainable fishing

1. Introduction

For the second half of the twentieth century, scientific and technological endeavours focused on finding new fisheries to exploit and more efficient and effective ways of harvesting. This was possible as developments in vessel and gear design, navigation and positioning systems and means to detect fish (e.g., depth-sounders) became more accessible to the common fisher [1]. These scientific and technological advances led to a dramatic increase in global fishing effort. Such developments also allowed fleets to exploit more distant resources to the point where the only unexploited fishery resources were those that remained physically inaccessible, for example under sea-ice [2]. For much of this period, much of the sea was treated as a common resource with many fish stocks exploited with little restriction and only a few with strict governance, setting conditions for a "tragedy of the commons" [3]. In recent decades, there has been increasing awareness of the need for global political action on natural resource management, as evidenced by the Rio Declaration on Environment and Development in 1992 [4] and by such initiatives as the Oxford Martin Commission for Future Generations, launched in 2012 by an interdisciplinary group of organisations [5].

By the latter decades of the twentieth century, it became apparent that the substantial increase in fishing capacity was leading to overexploitation and, in some cases, collapse of fisheries [6,7]. Overfishing, with associated ecosystem shifts, is a major threat to the marine environment. More than half of the world's marine fish stocks are considered to be either overexploited or fully exploited with no room for further expansion [8]. Although stocks have been fished for a number of centuries, the sheer number of global stocks that are currently below sustainable exploitation levels is unprecedented [8,9]. Failure to understand and sustain ecosystem processes, including human impacts upon them, continues to cause major biodiversity loss in many places around the globe [10–14]. As a result, a number of scientific initiatives are directed towards developing and applying methods to better measure, predict and monitor sustainable yields of key fish stocks, in both national and international waters [15,16].

1.1. Public Demand for Marine Management

Over at least two decades, there have been increasing calls from scientists, nongovernmental organisations (NGOs) and the public at large for better management of marine ecosystems. These calls have partly been based on scientific research that has revealed the myriad ways that fishing activities (along with climate change, terrestrial runoff and other anthropogenic processes) impact the overall health of marine ecosystems [9,17,18]. Increased environmental awareness has led to calls for attention to ecosystem-focused approaches to management, variously termed the Ecosystem Approach to Fisheries (EAF) [8], Ecosystem-Based Fisheries Management (EBFM) [19], or cross-sectoral Ecosystem-Based Management (EBM) (i.e., spanning all marine sectors, not just fisheries) [20].

Despite an increase in scientific knowledge and management efforts on overexploited fisheries and marine systems, there are still ecosystems and fish stocks showing no or little sign of recovery. It is recognized that impacts on the marine environment from fishing pressure might, in some cases, be more severe than first thought [21]. This calls for fisheries to be governed and managed holistically, needing a combination of environmental, biological and socioeconomic research to provide robust marine governance and management strategies to ensure a sustainable marine environment. The gap, however, between science and policy has been acknowledged [22,23], as has the fact that governance and management decisions are not always based on the best science available [24].

1.2. The Management Challenge: Predicting Uncertainties

Apart from fishing pressure, marine ecosystems and fisheries are also subject to other effects of human activity, such as climate change, ocean acidification and related biophysical impacts, habitat loss and impacts from terrestrial land use, such as land-based sources of pollution and litter [12,25,26]. A key challenge is to predict the long-term effects of these cumulative anthropogenic impacts and to form appropriate management strategies [27]. Without appropriate knowledge and understanding of the ecosystem supporting fisheries, and the communities in which fisheries are embedded, it is likely that management will fail [28].

The complexity of governing and managing fisheries in a socioeconomic context was illustrated by the 2009 Nobel Prize in Economics. The Nobel Prize was shared between Dr Ostrom, whose research was based on the assumption that people in a community can create successful agreements (and compliance) for managing common use of natural resources, such as fisheries [29], and by Dr Williamson, who presumed that natural resource management needs a top-down management approach because individuals ultimately cannot trust one another [30].

Another challenge (at times the largest challenge) for fisheries and environmental managers is a lack of political will to use and implement recommendations based on scientific findings. This challenge can reflect and reinforce the 'science–policy gap' [22]. Although scientists may make management recommendations based on their findings, ultimately management decisions are made by government officials and politicians. Importantly, these decisions are not driven only by scientific knowledge of the stock and dynamics of the ecosystem in which a fishery is embedded, but also by a range of political agendas and economic, social and cultural considerations. While scientists may be frustrated with this reality, it is important for them both to accept that they are only one voice at the decision-maker's table, but also not to shy away from objectively presenting the scientific evidence.

Given that there are many environmental, biological and socioeconomic factors that ultimately affect the state and health of the oceans, and that these drivers vary in time and space, decision-makers increasingly ask whether there is sufficient scientific information and knowledge of ecological functions and processes to implement an ecosystem approach to marine and fisheries management [31]. Successful marine management needs careful integration across sound scientific knowledge, development and implementation of management instruments and compliance tools. Even though there are many ecological processes to understand further, it is widely recognised that we do have sufficient scientific information to start implementing EBFM in many places around the world [32–34].

One challenge to implementing EBFM is that ocean resources are often managed sector-by-sector, i.e., coastal and terrestrial development, water management, environment conservation and primary industries (including fisheries) are each managed by separate jurisdictions [31]. The different set of goals and objectives within each sector may have implicit trade-offs so that fisheries managers often need to navigate and respond to conflicting objectives and incentives involving two or more government agencies [35,36] or interest groups. Clearly, if there is a negative impact on marine habitat due to fishing gear as well as from toxic terrestrial run-off, then both the fishing sector and the land-use sector need to take appropriate actions to prevent further habitat degradation [37]. Implementing EBFM, or EBM, requires a governmental organisational structure that matches this holistic view of ecosystem-based management. This does not immediately dictate an overarching, all-encompassing regulatory body, but it does necessitate communication (and where possible harmonisation of requirements) between agencies.

While defining the final scope of an ecosystem-based management governance system is beyond the scope of this paper, providing information on the current state of play is important to understanding what steps are still required to achieve solid advances. This research explores the main issues influencing the sustainability of fisheries. It draws on data derived from an international survey of fisheries experts, using the elicited responses to (1) identify the main issues in attempting to ensure the sustainability of fisheries, and (2) address how to begin to bridge the gap between scientific knowledge and the governance of marine systems, from the point of view of fishery management experts. The survey data were analysed to explore expert insights, opinion and understanding on the challenges to sustainable fisheries, the efficacy of tools used to manage fisheries and the complexity of interactions in fishery socioecological systems.

2. Methods

2.1. Data Collection

We targeted marine experts from around the world, primarily scientists and natural resource managers. Our survey was designed to elicit knowledge from marine scientists, managers, fishers and policy-makers. The intention was to gather specialist knowledge and experience in relation to sustaining fisheries. The survey was implemented by inviting experts to share their knowledge and experiences at the 6th World Fisheries Congress in Edinburgh, 8–11 May 2012. Attendees were invited to sit down at a booth and take part in the web-based survey. If an individual did not have time to conduct the survey when approached, they were given the opportunity to complete the survey in their own time either online or via a hard-copy of the survey. In total, 549 persons were invited to participate in the survey, resulting in 168 fully completed surveys (20 more provided partial completions that were still sufficient for inclusion in the analysis), giving a 34% response rate.

2.2. Analysis

The questions and a summary of the answers are presented in Appendix A. Given small sample sizes when respondents were broken down by category, for some questions, the responses from fisheries/natural resource managers and policy-makers were aggregated into a 'managers/policy makers' group. For the same reason, variables measured on five-point response scales were, in some cases, converted into a three-point scale. For example, the five-point 'satisfied-dissatisfied' scale was in some cases collapsed into the categories 'satisfied', 'neutral' and 'dissatisfied', by combining 'satisfied' with 'very satisfied', and 'dissatisfied' with 'very dissatisfied'.

Statistical analyses, including crosstabulations, were conducted using SPSS (Version 25.0., IBM Corp, Armonk, NY, USA). No corrections were made. The statistical independence of pairs of variables was analysed using the 2-factor G-test for independence at a 95% significance level.

3. Results

3.1. Demographics

The respondents were from 34 nations, representing scientists, fisheries managers, fishers, policy-makers, NGOs and others. Forty (40) respondents were from Australia, as the survey was trialed there before presenting it at the World Fisheries Congress.

Seventy-one percent of the respondents were male, and 60% of the respondents were 35–64 years old (Appendix A). Forty-two percent of the respondents had a Doctoral degree, 28% a Master's degree, 14% a 3–4 year university degree, and the remainder did not hold a degree, but all had completed high school (Appendix A). The majority of the respondents were scientists (Figure 1), with fifty-nine percent of the respondents holding a degree in marine science and 20% in environmental science. Other respondents had degrees in business, law, economics and social sciences (Appendix A).

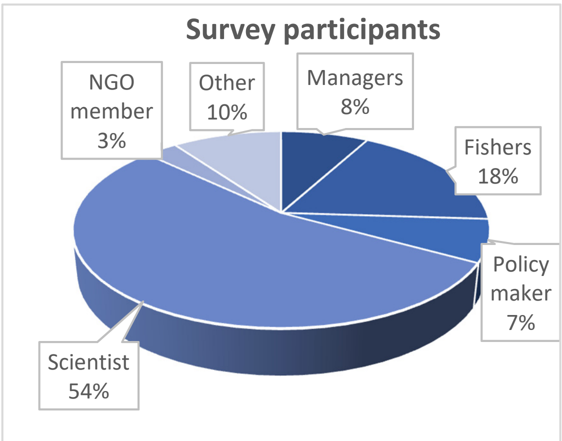

Figure 1. The breakdown of respondents by profession (n = 177). 'Other' includes consultants, economists, social scientists, lawyers and students. NGO, nongovernmental organization.

The majority of the respondents spanned middle-executive management positions, and represented pelagic, demersal, coastal and crustacean fisheries (Figures 2 and 3). The respondents represent experience and knowledge from fisheries deemed to be sustainable as well as from overfished, collapsed, recovering and exploratory fisheries (Figure 4). Of the respondents, 47% worked with national management agencies, 24% with international management and 15% at universities (Appendix A).

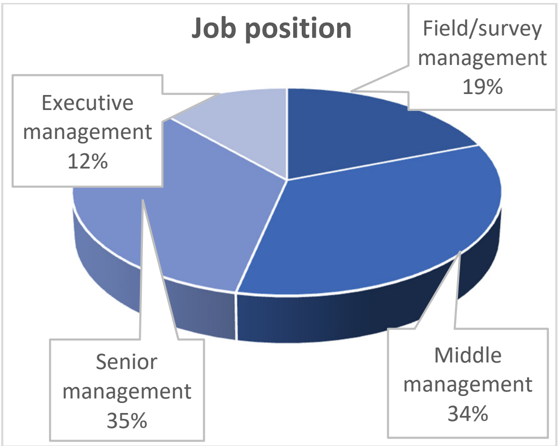

Figure 2. The job position held by respondents (n = 146).

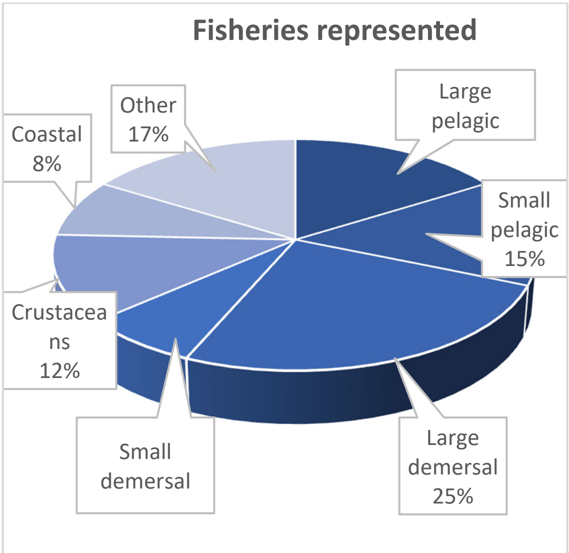

Figure 3. The fishery types covered by survey respondents. 'Other' includes shark, inland, aquaculture and shellfish (n = 143).

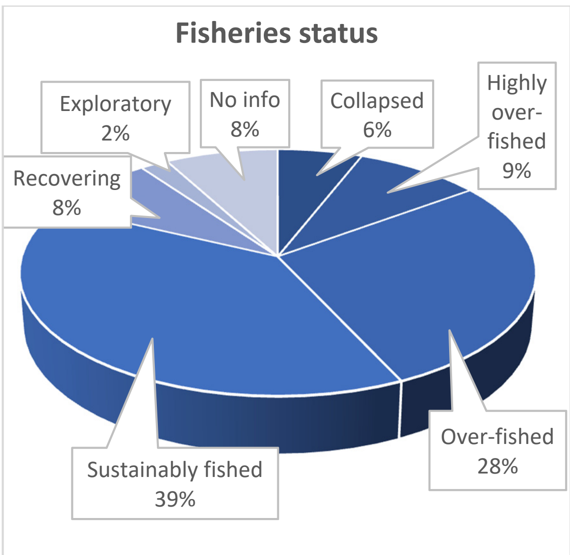

Figure 4. The status of the fisheries the respondents are working with (n = 172).

3.2. Anthropogenic Effects on Fisheries and Marine Systems

Overfishing, climate change and habitat destruction were believed to be the three threats most affecting fisheries, both at national and global scales (Figure 5). There was no significant difference among the responding groups as to whether or not they perceived the same 10 threats as major threats to national and world fisheries (G = 10.191, df = 9, p = 0.335), where G is the likelihood-ratio, df the degree of freedom and p the probability value.

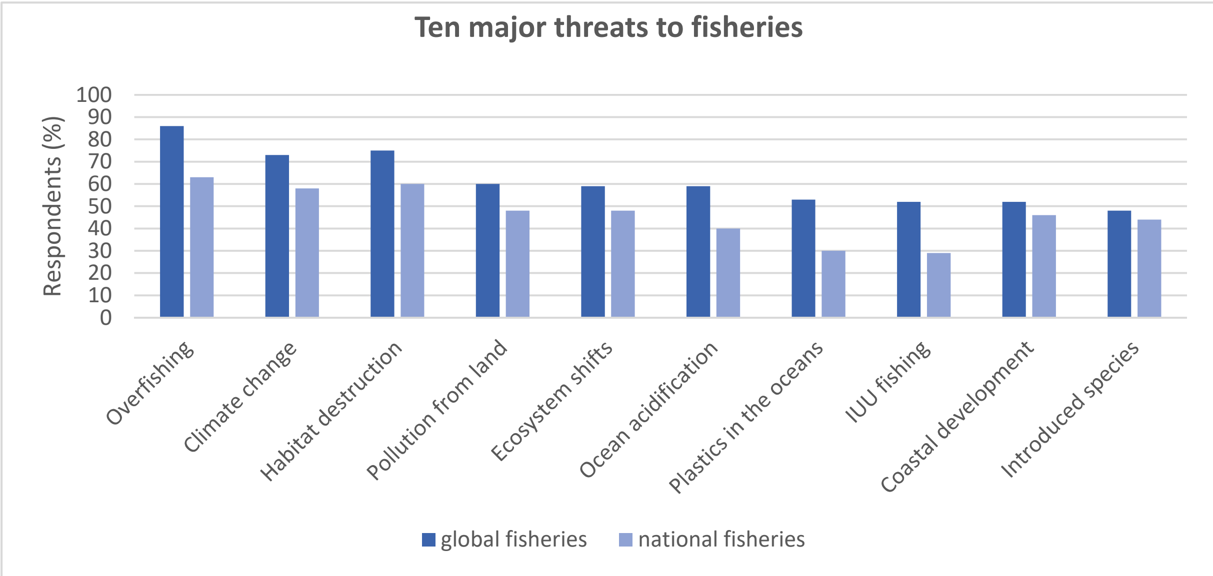

Figure 5. The 10 major threats to national and global fisheries (n = 164).

Overfishing was believed to be a major threat to world fisheries by 79% of the managers, 92% of the policy-makers, 79% of the scientists and 84% of the fishers (Figure 5). Notably, 69% of the policy-makers and scientists said they believe that illegal, unreported and unregulated (IUU) fishing is not a major threat to national fisheries, while 78% of the fishers said they think it is.

Fifty-eight percent of all respondents believed climate change to be a major threat to national fisheries, while 59% believed that ocean acidification is a major threat to world fisheries and 40% to national fisheries. Seventy-two percent of the fishers said they think habitat destruction is a major threat to the marine environment for world fisheries, while only 13% said it is a threat to national fisheries. Forty-one percent of the scientists believed land-based pollution is a major threat to fisheries, compared to 84% of the fishers, 85% of the policy-makers and 79% of the managers. Of all the respondents, 46% said plastic is a major threat to world fisheries (57% of managers and 62% of the scientists) and 30% said it is a major threat to national fisheries.

Despite the divergence in views in the earlier question pertaining to whether IUU is a threat to international or national fisheries, there was no significant difference among the responding groups on how they viewed the specific aspects of IUU fishing (G = 61.275, df = 45, p = 0.054). Corruption was seen as the main aspect of IUU fishing (66%), with 55% of respondents believing that there is insufficient compliance in place to combat IUU fishing (Figure 6). Sixty-four percent said they believe IUU fishing is a problem within their fishery, and of those 43% said they think IUU fishing amounts to 6–30% of the total catch (Appendix A). When specifically asked about IUU (rather than ranking it against other threats), on a global scale, 99% of the respondents believed that IUU fishing is a problem and 65% estimated the global level of IUU fishing to be between 31–60% of the total catch worldwide (Appendix A).

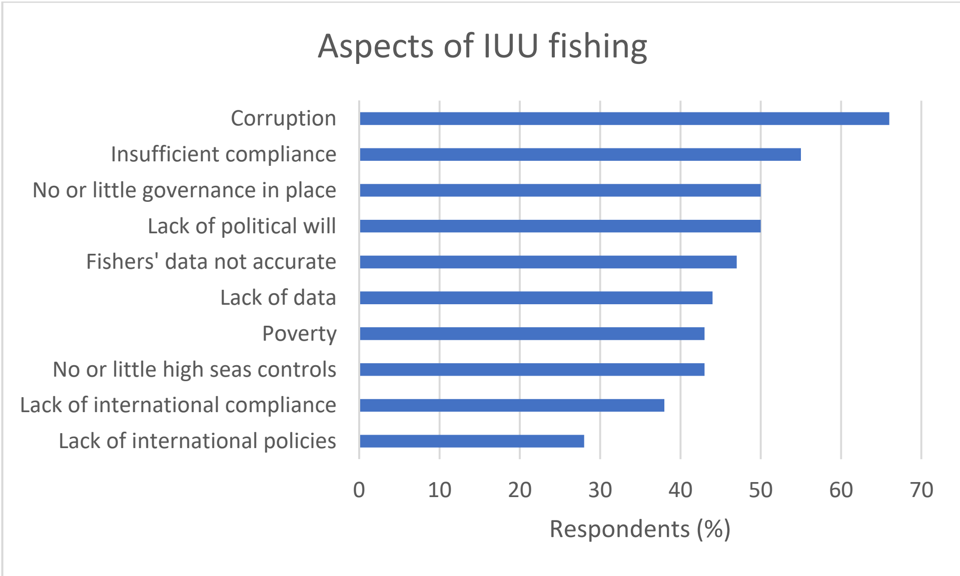

Figure 6. Key aspects of illegal, unreported and unregulated (IUU) problems identified by the respondents.

3.3. Fisheries Governance and Management Affecting Fisheries and Marine Systems

On the question of what the three main challenges to fisheries are, the following four factors ranked the highest: a lack of political will (56%); not enough compliance with regulations (33%); overfishing (29%); and stock assessment and monitoring (28%) (Figure 7). There was no significant difference among the responding groups regarding which of the four factors were seen as the main challenges to managing fisheries (G = 23.409, df = 15, $p = 0.076$). Despite compliance being listed as a major challenge to sustainability, 90% of the fishers and 66% of the scientists said there is already enough compliance.

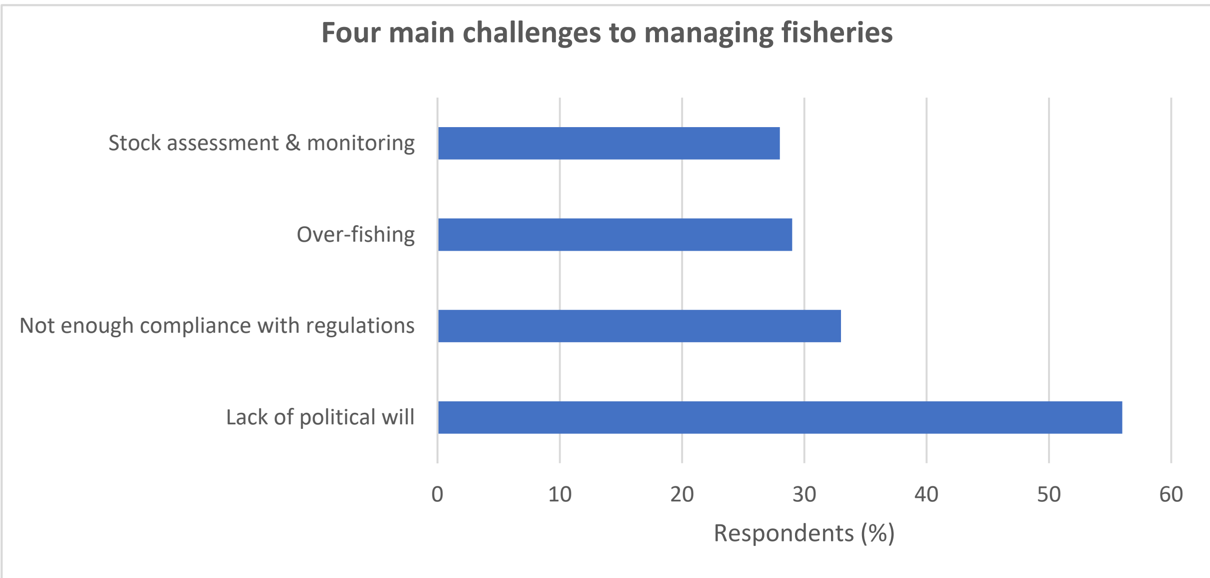

Figure 7. Expert opinions on four main challenges to managing fisheries (n = 174).

Fifty-five percent of the respondents believed that, during the course of their careers, they have seen major changes in fisheries management, such as increased input from scientists and industry, and stakeholder collaboration (Figure 8).

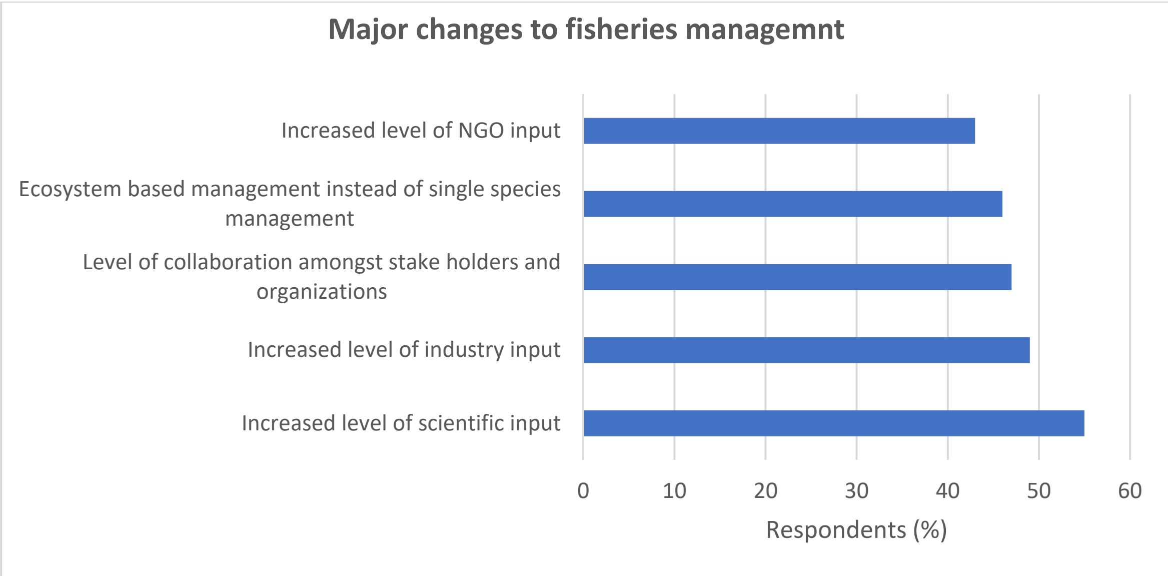

Figure 8. Major changes that have occurred in fisheries management during the respondents' careers in fisheries (n = 109).

More of the respondents were satisfied than dissatisfied with the planning and implementation of the EBFM processes. However, when considering the results of EBFM, a greater number of respondents were neutral, out numbering those who were satisfied or dissatisfied (Figure 9). When looking to the fisheries they knew best, 60% of the respondents said that the fishery they worked with has implemented (EBFM) (Appendix A), or a similar holistic approach to governing fisheries, though 50% said they were unsure as to whether the implementation of EBFM has been successful (Figure 10).

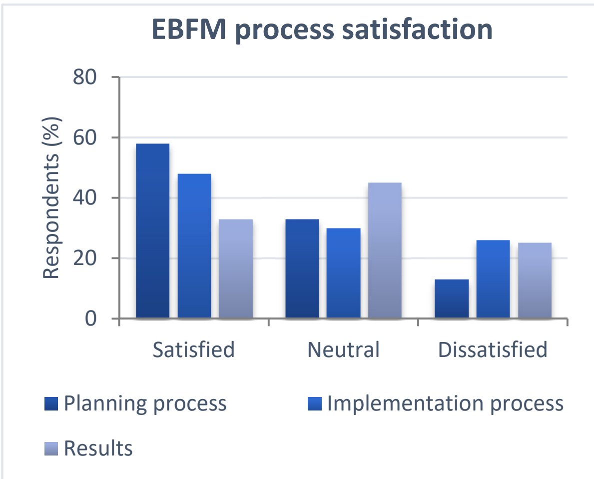

Figure 9. Measuring how satisfied the respondents were with the whole Ecosystem-Based Fisheries Management (EBFM) process (n = 104).

There was no significant difference among the responding groups in terms of their satisfaction with the planning processes associated with implementing EBFM (G = 11.358, df = 10, p = 0.33), with 73% of the managers, 67% of the policy-makers, 47% of the scientists and 50% of the fishers being satisfied. Thirty-eight percent of the scientists and 50% of the fishers were neutral. When it came to taking the step of implementing EBFM, there was also no significant differences among the responding groups on how they felt regarding this implementation process (G = 21.174, df = 15, p = 0.131), with approximately 50% of both the scientists and fishers being neutral.

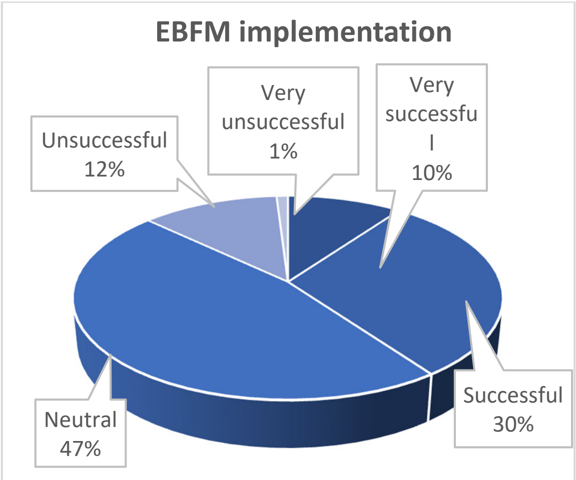

Figure 10. The perception of those respondents who said the EBFM process has been implemented regarding how successful the process had been (n = 107).

Sixty-four percent of the managers and 58% of the policy-makers were satisfied with the results of implementing EBFM, compared with 31% of the scientists, 46% of the fishers and 0% of the NGOs (Table 1). About as many scientists as managers thought the implementation process of EBFM had been unsuccessful (Table 1) and about as many fishers as scientists remained neutral as to whether the EBFM implementation process had been successful (Table 1).

Table 1. The level of success for the implementation process of EBFM per responding group (% within each responding group. n = 108).

	Managers	Policy-Makers	Scientists	Fishers	NGOs
Very successful	0%	15%	11%	11%	0%
Successful	64%	31%	20%	35%	0%
Neutral	18%	39%	50%	54%	67%
Unsuccessful	9%	15%	19%	0%	33%
Very unsuccessful	9%	0%	0%	0%	0%

Once EBFM is in place (often in an adaptive management context), it is important to know if it is proving successful. When asked about this, there was no significant difference among the responding groups regarding how satisfied they were with the results of EBFM (G = 16.571, df = 10, p = 0.084): 55% of the managers were satisfied, compared with 23% of the scientists (Table 2). Of the fishers, 65% were neutral and 67% of the NGOs were dissatisfied (Table 2). Figure 11 shows that EBFM is challenging to implement, mainly because the process is highly complex.

Table 2. Satisfaction among the responding groups regarding results of the implementation of EBFM (% within each responding group. n = 104).

	Managers	Policy-Makers	Scientists	Fishers	NGOs
Very satisfied	0%	25%	2%	8%	0%
Satisfied	55%	17%	21%	23%	33%
Neutral	27%	33%	41%	65%	0%
Dissatisfied	9%	25%	29%	4%	67%
Very dissatisfied	9%	0%	7%	0%	0%

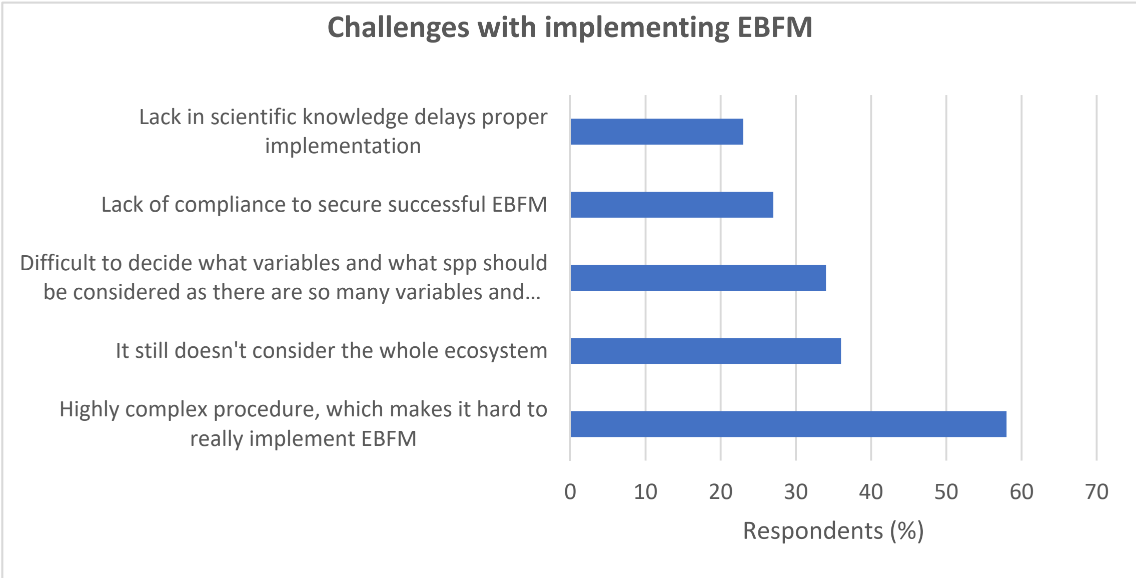

Figure 11. Implementing EBFM is a complex task (n = 83).

There was a significant difference among the responding groups regarding which tools are most efficient for implementing EBFM (G = 44.226, df = 20, p = 0.001). Respondents viewed good science, Marine Protected Areas (MPAs), individual transferable quotas (ITQs), gear restrictions and stakeholder participation to be the five most efficient tools for Ecosystem-Based Fisheries Management (Figure 12).

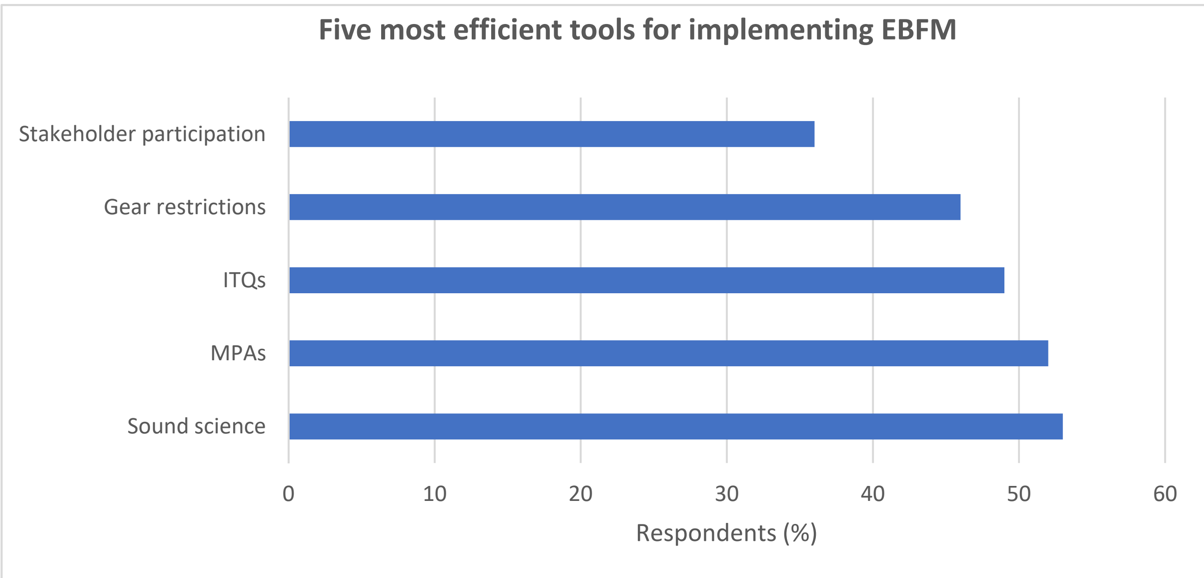

Figure 12. Participants' responses to the five most-efficient regulations for Ecosystem-Based Fisheries Management (n = 121). ITQs, individual transferable quotas.

3.4. Improvements Needed to Obtain and Maintain Sustainable Fisheries

For the question on what type of organisation would be optimal for implementing EBFM, 83% believed that a mix of a top-down and bottom-up management is optimal (Appendix A). When it came to what more is needed to sustain fisheries, 72% of all respondents answered they believe a stronger political will is needed to achieve successful ecosystem-based management (Figure 13).

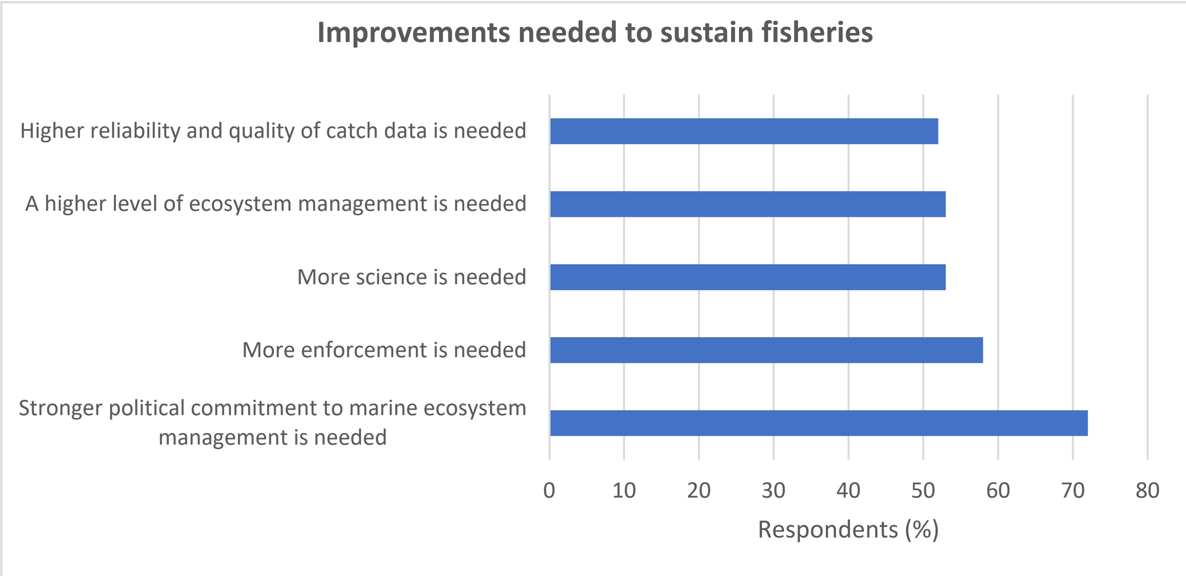

Figure 13. Improvements needed to obtain/maintain sustainable fisheries (n = 165).

There was no significant difference among the responding groups regarding which improvements are needed to sustain fisheries (G = 5.747, df = 20, p = 0.999), with all groups identifying the same mix of factors. However, this congruence did hide some differences in detail. Amongst managers, a clear majority (79%) stated that stronger political will is needed. A majority of managers (60%) also said they think more enforcement is needed; this latter result is in sharp contrast to the 25% of fishers who felt the same way. Overall, 53% of the respondents believed that more science is needed in order to obtain and maintain sustainable fisheries (Figure 13).

The majority of the respondents were supportive of input controls, such as by-catch reduction devices, size limits, spawning and spatial closures, regional zoning, seasonal closures and gear restrictions (Figure 14). The majority of the respondents also showed support for output controls, such as total allowable catch (86%), individual transferable catch (69%) and bag limits (69%) (Appendix A).

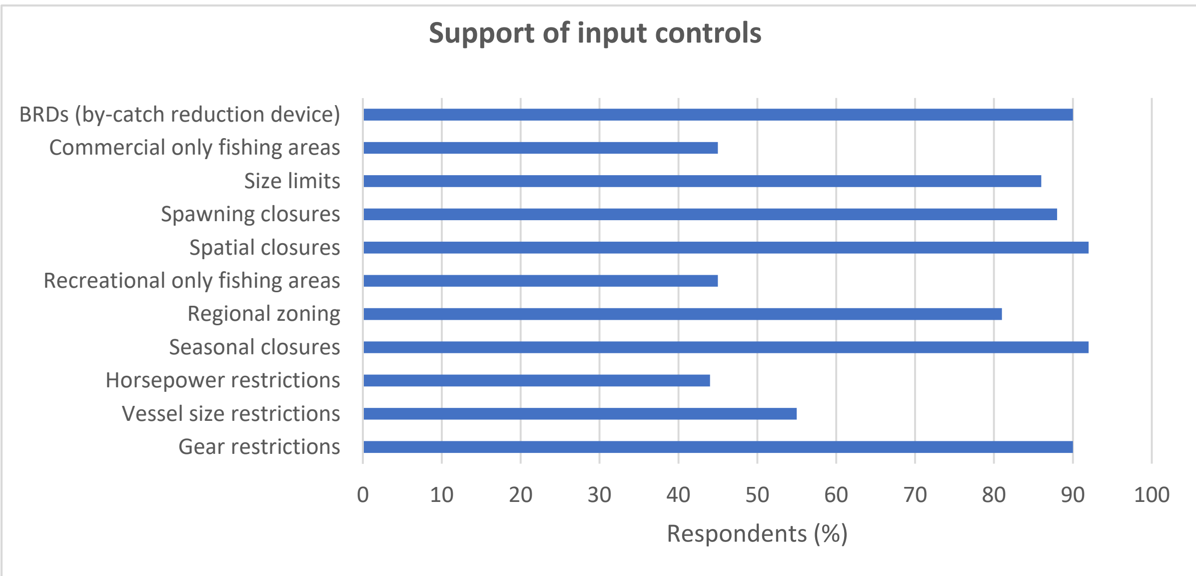

Figure 14. The level of support for several input controls shown by marine experts (n = 162).

When it came to monitoring and assessing stocks, Catch Per Unit Effort (CPUE) was the most common method used for measuring fish abundance (Figure 15), although logbook data was considered a close second.

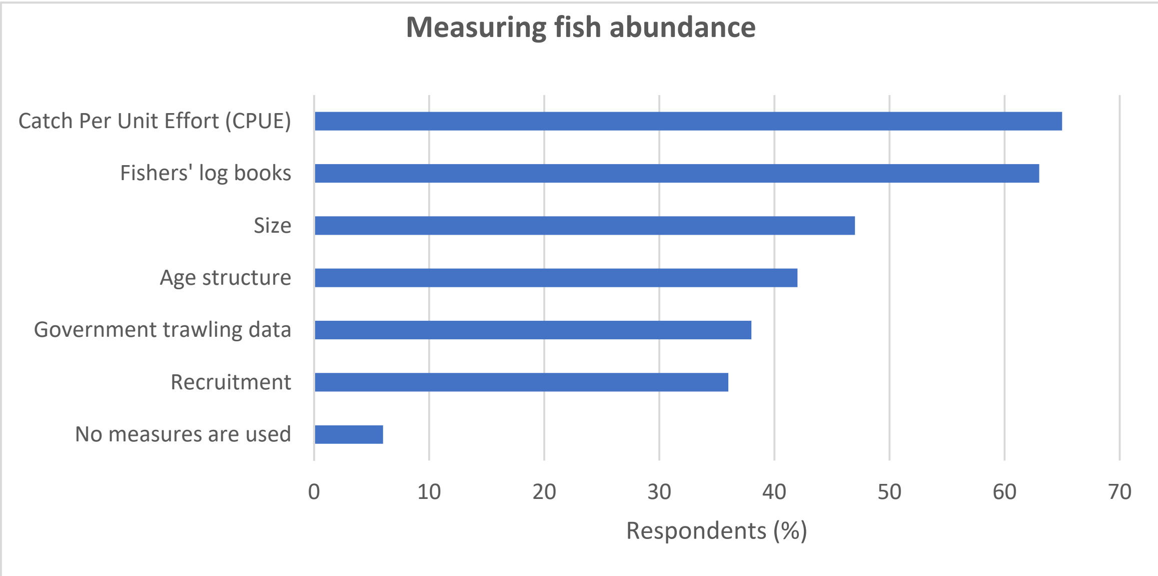

Figure 15. The prevalence of different approaches to measuring fish abundance.

Experts were asked to identify what they see as the main challenges to sustainable fisheries and what management tools would be generally useful for combatting challenges in fisheries (Table 3). Interestingly, while the challenges included things that are beyond the scope of fisheries management alone (e.g., land-based pollution or plastics), all of the suggested tools are classical fisheries management tools. When asked the question regarding why regulated fisheries are still faced with overexploitation, the highest ranking responses were: (1) the need for more scientific information; (2) existing science not being used to its fullest; and (3) a lack of political will. There was no significant difference to these three reasons among the responding groups (G = 2.001, df = 10, p = 0.996). The vast majority of all responding groups (regardless of background) said that the lack of political will is a major reason why regulated fisheries are still faced with overexploitation (Table 4).

Table 3. Ten main challenges and ten main tools for sustaining fisheries (n = 133).

Ten Fisheries Challenges	Ten Tools for Sustain Fisheries
Overfishing	Seasonal closures
Climate change	Total Allowable Catch (TAC)
Habitat destruction	Size limits
Pollution from land	Spatial closures (e.g., MPA)
Ecosystem shift	Ecosystem-Based Fisheries Management (EBFM)
Ocean acidification	Spawning closures
Plastics in the oceans	Mesh size
IUU fishing	Individual Transferable Quota (ITQ)
Coastal development	By-catch reduction device
Introduced species	Regional zoning

Table 4. Major reasons for why regulated fisheries are still faced with overexploitation.

	Managers	Policy Makers	Scientists	Fishers	NGOs
Not enough scientific information	72%	54%	78%	73%	80%
Scientific knowledge is not fully being used	64%	67%	53%	62%	20%
Lack of political will	93%	92%	74%	84%	80%

3.5. Socioeconomic Situations Affecting Fisheries and Marine Systems

Forty-two percent of the respondents said fish as a protein source is not important for survival in their country, 7% said it was, and 23% considered fish vital for some regions (Appendix A). However, when questioned on how important fishing is as a main source of income, 65% of the respondents said fishing is the major economic activity for a few regions, 42% said fishing is a vital source of income for some regions and 37% said that fishing is somewhat important as a main source of income for the country as a whole (Appendix A). Regarding subsides, 52% of the respondents said that fisheries subsidies are available in their country, 34% said there are no subsidies and 14% did not know (Appendix A). Of those who said there are subsidies in their country, 88% said they have fuel subsidies, 35% have employment subsidies, 26% have lower interest rates on bank loans and 15% said they have subsidies related to culture. Sixty-five percent of the respondents believed that subsidies contribute to overcapacity of the fishing industry (Figure 16).

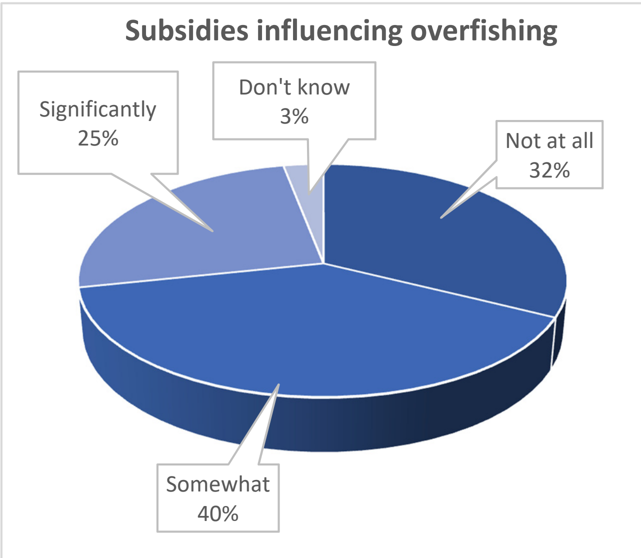

Figure 16. Respondents' belief regarding whether subsidies contribute to overcapacity of the fishing industry (n = 87).

There was particular support amongst the respondents for economic incentives, such as fishing access agreements and fishing vessel buy-backs by the government (Figure 17).

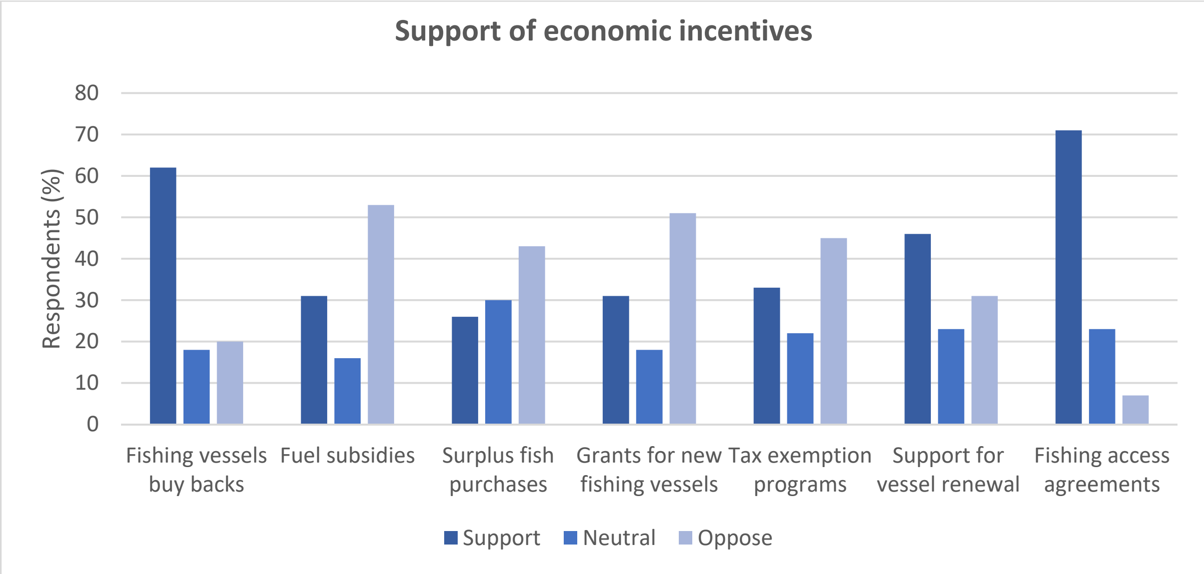

Figure 17. Experts showed large support for fishing vessel buy-back schemes and fishing access agreements (n = 168).

Fifty-one percent of the respondents were not able to estimate the cost of management for the fishery they work with (Appendix A).

4. Discussion

Results from the survey demonstrate that the respondents have had extensive experience in the fisheries management process, including both science and management. The respondents had formal qualifications and/or experience; with 42% having Doctoral degrees, 28% Masters degrees and almost half of the respondents having senior or executive roles in fisheries. The coverage was also global, representing 34 nations in total. While we acknowledge the sample sizes were uneven, with more scientists answering than any of the other respondents, there was congruence in many results, suggesting that perceptions held by fisheries scientists and managers may not actually be that different. Indeed, in many cases, fishers also held similar attitudes, though there were some notable differences (e.g., on the need for additional enforcement). In following up on why it proves so hard to access the opinions of managers, let alone policy-makers (who were an even smaller respondent group), it became clear that they lack opportunities to gather and share information in the same way as provided by scientific conferences. Funding such travel is often hard to do. In improving the state of fisheries globally—sharing insights into what has and has not worked—it appears that there is a fundamental need for the creation of a fora, or a conduit, for information sharing amongst these managerial and policy groups.

4.1. Threats and Challenges in Sustaining Fisheries

This analysis clearly confirmed that sustaining fisheries is a complex challenge, but the experts also offered their opinions as to how to combat the issues involved, which are generally consistent with the literature on how to sustainably manage fisheries [37–40]. The respondents considered the 10 main threats to fisheries to be overfishing, climate change, habitat destruction, pollution, ecosystem shifts, IUU fishing, ocean acidification, costal development, land-based pollution and introduced species. These same threats were considered important at national and global scales. This shows that the threats and challenges to sustaining fisheries are similar around the world; a finding consistent with existing scientific literature [8,41–43].

4.2. Management Tools in Sustaining Fisheries

Although the analysis highlights an extensive range of challenges in achieving sustainable fisheries, it also shows that the respondents believe there are many existing tools for addressing these obstacles and supporting sustainable fishing. Just as the main challenges and threats to sustaining fisheries were viewed similarly around the world, so too the list of potential tools was consistent across respondents from differing backgrounds and nationalities. While overfishing was seen as a major threat to sustaining fisheries (nationally and globally), the majority of all responding groups said it is not a challenge to manage. Given concern over the magnitude of the problems facing "small scale" fisheries and the difficulties of achieving successful management in locations with few regulatory resources [44], this is a surprising response. However, this may be because the respondents primarily work in fisheries with a range of regulations in place, with compliance and enforcement mechanisms already implemented to combat this challenge and so they have directly experienced the management of overfishing. This result may highlight a tacit bias in the work—people working in less well-resourced fisheries are unlikely to have had the means to visit the Congress where the survey was undertaken—and future follow-up on this work should endeavour to address this gap.

Tools identified as useful in sustaining fisheries included sound science, input controls (gear restrictions, seasonal closures, spatial closures, spawning closures, by-catch reduction device, size limits and regional zoning), output controls (bag limits, ITQs, Total Catch Limits (TACs)), a mixture of top-down and bottom-up organisation, stakeholder participation, fishing access agreements and fishing vessels buy-backs, effectively taking an integrated or ecosystem approach. In particular, the vast majority of all responding groups viewed good science, MPAs, ITQs, gear restrictions and stakeholder participation to be the five most efficient tools for Ecosystem-Based Fisheries Management. All of these tools are consistent with what have been recorded as good supporting tools for sustainable fisheries in other research [39,45–47].

More of the respondents were satisfied than dissatisfied with the EBFM's planning and implementation processes. More were, however, neutral regarding the results of the EBFM, reflecting in part the complex nature of the EBFM process. Management tools might be put in place, but it may take a long time before any results are seen. These approaches may be introduced when the system has been overfished and shifted to a state where restoration may take a lengthy period [48–50]. More managers than any other responding group said they believed the EBFM implementation process was a success. About the same number of managers, policy-makers and scientists said they believed it was unsuccessful. Possibly, there were different expectations among the various responding groups, where the managers saw it as a success in itself that such a large management process had been adopted and implemented by the government in the first place; while the scientists may have been more cautious (neutral) because any biological success was yet to be seen. More managers and policy-makers said they were satisfied with the results of EBFM than the scientists and fishers, although all responding groups showed a cautious element to any success, the fishers more so than any other group. Again, the expectations are likely to differ among the various stakeholders, as implementing EBFM unavoidably involves trade-offs in meeting all biological, economic and social goals [51], which will differ between the different groups.

Given the growing focus on the implications of a high level of marine pollution [52–54], it might be surprising that only just over half of the respondents answered that they believe land-based pollution is a major threat to the world's fisheries and 46% said plastic is a major threat. This might be due to the fact that the survey was undertaken in 2012 when there was not as much scientific reporting on plastics in the ocean [55]. It was particularly noteworthy though that, despite pollution and plastics being identified as threats, few, if any, of the suggested tools put forward are likely to have a significant role in combating these issues. This indicates that, while awareness of the issue is growing, focus is still on the classical threats and long-established tools.

4.3. Management Constraints in Using More Science

Fisheries management in the majority of industrialised nations is said to be science or evidence-based, even if science-based advice is not always followed in the political process [56]. This analysis showed 'not using scientific knowledge to its fullest potential' to be the main constraint for effectively and efficiently implementing ecosystem-based fisheries management, together with: (1) a lack of compliance; (2) IUU still being a major global issue; and (3) political will.

The management of marine systems in general, and fisheries in particular, is highly complex and a story of information paucity. It is very difficult to estimate even the abundance of target species. In some regions, it is even difficult to precisely determine what has been extracted from the ocean, let alone the effects on dependent species or species not directly impacted by fishing [57]. The reason why science is not being used to its fullest is interesting. Is it because of a disconnect of science and management? In Australia, having fisheries scientists work closely with but ultimately sit apart from the management agency has been a successful approach, as the participatory processes in place there allow for communication, while the 'distance' has helped increase trust in science and motivation of scientists by all stakeholders. In other regions, the organisational disconnect has led to barriers to information uptake. In these latter instances, because scientists belong to a separate organisation, they are treated more as a consultant and thereby not fully integrated in the management process, leading to critical communication failures. An example of this is where scientists from the International Council for the Exploration of the Sea (ICES) advise the Oslo Paris Commission (OSPAR), the Helsinki Commission, the Baltic Marine Environment Protection Commission (HELCOM), the North East Atlantic Fisheries Commission (NEAFC), the North Atlantic Salmon Conservation Organization (NASCO) and the European Commission (EC) [58]. Yet, despite all of these channels, the decisions have still been largely political, leading to overfishing within the European Union [59–62]. More recently, there have been significant efforts to reverse this, though it has only been patchily effective; the Mediterranean, in particular, still has a majority of its stocks in an overfished state [63].

An alternative example is found with the Commission for the Conservation for Antarctic Marine Living Resources (CCAMLR). CCAMLR has its scientific committee with its working groups fully integrated in the organisation advising the commission at the annual meetings. Many participants are a part of both the scientific commission and the commission [64–67]. This science-based commitment to ecosystem-based management has, since 1982 (when CCAMLR was founded), contributed to the recovery of previous overfished stocks, and sustainable management of the Southern ocean ecosystems, including fisheries [39,68,69].

4.4. A Brief Comment on Cognitive Inconsistencies

With the growing accessibility of literature regarding human cognition, it would be remiss of us not to note how the perceptions reported in this survey may be effected by common cognitive biases and fallacies [70,71]. We are not trained professionals in the field of psychology, so will not go into depth, but the results for IUU appear to be a stand out example of such biases in action. There is clear recognition that IUU is a problem, with almost complete consensus on this point across respondents. However, it appears that the perception of the magnitude of the problem is strongly influenced by an optimism bias (with far fewer respondents thinking it is a problem in their own fishery) and by biases to do with framing (it is seen as more of an issue when asked directly about IUU rather than in general bundled with other risks) and uncertainty (as the true magnitude of the problem is typically unknown and so may be discounted as a result). In addition, the fact that the suggested solutions for sustainable fisheries include a list of existing tools, many of which have been in use in fisheries for centuries, suggest that there may be a strong endowment effect, with experts sticking strongly to tools they are already heavily invested in without necessarily looking for new alternatives. This is worth additional research to verify. If confirmed, it would open up new research paths; if falsified, then it would reassure all stakeholders that we already have at hand all the tools we need to achieve sustainable fisheries.

4.5. Political Will to Match Biological Challenges

The survey showed that, despite implementation of EBFM and increased levels of input from science, industry and NGOs, sustaining fisheries remains a challenge. The main challenge when managing fisheries was said to be a lack of political will. We note that policy-makers represented just 7% of the respondents, and the issue of sustaining fisheries due to a lack of political will might have been viewed differently had there been more policy people participating in the survey. Indeed, knowledge brokers who span the science–policy interface caution that policy-makers can become frustrated with scientists who fail to appreciate the many sources of information and many pressures that must be navigated by policy-makers when making a single decision [72]. Political advisers and politicians must also consider political, social, cultural and economic matters.

The challenge to managing fisheries ranked second by the respondents was a shortage in compliance and regulations, stock assessments and monitoring. This might not come as a surprise as there are high costs involved for scientific assessments and controlling regulations [73]. In linking the top two challenges, the challenge found regarding the lack of compliance may reflect a lack of general political and social will to fund and implement required management controls [70]. Politicians may be more inclined to act on issues more important to the voters (who have concerns extending well beyond fisheries), and perhaps, at times, they do not either fully appreciate the seriousness of the marine issues or the need for long-term sustainable plans that span many election cycles.

However, what might not be high on the political agenda today may change with building public awareness, which in turn may demand better management of natural resources [71]. The United Nations' Ocean Conference for implementation of Sustainable Development Goal 14 ('Conserve and sustainably use the oceans, seas and marine resources for the sustainable development') is an example. This conference was held in June 2017, with 193 nations making a commitment to a set of measures aiming to increase the resilience of ocean health. These pledges have been accompanied by over 1400 voluntary commitments. Together, these commitments can be seen as a global commitment (raised from increased scientific and public pressure) for politicians to better manage marine life. Given increased consciousness of environmental issues among the public since this survey was conducted [72,73], it would be interesting to conduct a similar survey today to see if there is a perception of a stronger political will today to sustain fisheries.

5. Conclusions

This study reinforces the magnitude of the challenges in sustaining fisheries. It identified key issues underpinning the use of an ecosystem management approach, such as complexity, the high degree of connectivity, difficulties associated with observing ocean processes and monitoring flora and fauna. The fact that 99% of the respondents believed that IUU fishing still is a global problem and 65% estimated the global level of IUU fishing to be between 31 and 60% of the total catch worldwide is, naturally, a major concern. Tools identified as useful in sustaining fisheries included sound science, gear restrictions, seasonal closures, spatial closures, spawning closures, by-catch reduction device, size limits and regional zoning, bag limits, ITQs and TACs. The study indicated that the common position of the respondents is that the use of a mixture of top-down and bottom-up organisation and institutional forms is important to success, as is the importance of stakeholder participation. However, implementing these solutions will come with new challenges, especially when implementing them at scales aligning with the magnitude of participation in "small-scale" (often poorly resourced) fisheries in developing nations. The survey also highlighted the impact of fishing access agreements and fishing vessels buy-backs as tools to constrain effort. Again, these are things that may work more effectively for industrial than some artisanal fisheries.

This research illustrated a clear perception of a need for a higher political will and commitment to combat challenges, such as IUU fishing, habitat destruction and climate change, both nationally and globally. More research and long-term monitoring to assist managers in prioritization resources was also identified as a particularly important need. It was clear from the analysis that the widely held belief by those experts in charge of the world's fisheries that, to recover from overfishing and fisheries collapse (and to minimise the future risk of such events), scientific input must be matched with the same level of political commitment, including implementing science-based fisheries and conservation measures.

It is also worth noting that human cognition is not infallible. When asked directly about illegal, unreported and unregulated fishing, 99% of the respondents saw it as a global issue; however, when put against other challenges, close to 70% of the policy-makers and scientists believed that is not a major threat to national fisheries, despite the fact that almost 80% of the fishers said they think it is. This suggests that there is a gap in the discourse and management of IUU fishing that likely needs closer consideration or discussion.

This analysis showed that there is the strong perception that scientific knowledge is not being used to its fullest potential and that in turn is the main constraint for effectively and efficiently implementing ecosystem-based fisheries management. Is the challenge then a lack of political will only, or is this a reflection of the make-up of respondents: scientists frustrated with a perceived lack of political appreciation? Perhaps there is a greater need to establish science-management networks that meet regularly, to train a new generation of scientists who have direct industry and regulatory body experience (spending time in both as well as academia before completing their training), as well as a need for scientists to communicate science in a more pedagogical way?

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Appendix A

Fisheries Governance Survey, with responses

Q1. Threats to the marine environment: For each of the potential marine threats, please tell if you believe there is no threat, a minor threat or a major threat.

Responses to the Fisheries Governance Survey are Presented in the Order the Questions Appeared in the Survey Instrument. I Have Read the Information Above and Consent to Participate in This Study. I am over the Age of 18 Years. Answer	Response	%
Yes	188	100
No	0	0
Total	188	100

No threat

Question	National Fisheries	World Fisheries	Total Responses
Pollution sourced from land	9	4	13
Eutrophication	19	16	35
Anoxic events	23	20	43
Ocean acidification	14	8	22
Introduced species and pests	5	5	10
Dead marine zones	25	14	39
Energy exploration	33	21	54
Ecosystem shifts	11	5	16
Habitat destruction	8	0	8

Question	National Fisheries	World Fisheries	Total Responses
Plastics in the oceans	23	12	35
Coastal development	14	16	30
Overfishing	12	0	12
Climate change	6	3	9
IUU fishing	9	1	10

Minor threat

Question	National Fisheries	World Fisheries	Total Responses
Pollution sourced from land	83	65	148
Eutrophication	95	76	171
Anoxic events	95	78	173
Ocean acidification	79	61	140
Introduced species and pests	91	79	170
Dead marine zones	92	83	175
Energy exploration (oil, gas, etc.)	87	84	171
Ecosystem shifts	74	63	137
Habitat destruction	57	41	98
Plastics in the oceans	94	62	156
Coastal development	75	61	136
Overfishing	49	32	81
Climate change	63	46	109
IUU fishing	40	14	54
Other, please specify	4	5	8

Major threat

Question	National Fisheries	World Fisheries	Total Responses
Pollution sourced from land	78	98	176
Eutrophication	56	65	121
Anoxic events	48	53	101
Ocean acidification	65	96	161
Introduced species and pests	72	78	150
Dead marine zones	46	63	109
Energy exploration (oil, gas, etc.)	45	63	108
Ecosystem shifts	78	97	175
Habitat destruction	98	123	221
Plastics in the oceans	49	87	136
Coastal development	76	85	161
Overfishing	103	141	244
Climate change	95	119	214
IUU fishing	47	86	133
Other, please specify	13	19	32

Q2. In your experience, what are the three main challenges of managing fisheries? Please add a brief description.

Answer	Response	%
Lack of political will	98	56%
Not all stake holders are involved	34	20%
Not enough compliance with regulations	57	33%
Fisheries are very complex to manage	29	17%
International cooperation is needed	25	14%
Over-fishing	51	29%

Answer	Response	%
Lack of knowledge in fish behaviour	11	6%
High amounts of by-catch and discard	30	17%
Poverty	14	8%
Stock assessment and monitoring	49	28%
Need to track trading of fish products	12	7%
Growing human population (food security)	22	13%
Take high levels of uncertainty into account when setting quotas	12	7%
Ecosystem management	24	14%
Consider socio-economic implications in poorer regions	21	12%
Impacts of climate change	20	11%
Amount of IUU fishing is underestimated	37	21%
Stakeholder agreements	19	11%
Other	39	22%

Q3. In what country do you work?

Answer	Response	%
Argentina	2	1%
Australia	40	24%
Bangladesh	1	1%
Canada	5	3%
China	1	1%
Czech Republic	1	1%
Denmark	1	1%
France	4	2%
Germany	2	1%
Greece	1	1%
Iceland	4	2%
India	1	1%
Indonesia	2	1%
Ireland	1	1%
Italy	3	2%
Japan	3	2%
Kenya	1	1%
Mexico	3	2%
Mongolia	1	1%
Namibia	5	3%
Netherlands	3	2%
New Zealand	2	1%
Nigeria	5	3%
Norway	2	1%
Philippines	2	1%
Saudi Arabia	1	1%
South Africa	5	3%
Spain	1	1%
Sweden	8	5%
Tanzania	1	1%
Turkey	2	1%
Uganda	1	1%
United Kingdom	30	18%
United States	21	12%
Total	170	100%

Q4. What is your role in fisheries?

Answer	Response	%
Fisheries manager/Natural resource manager	14	8%
Fisher	31	18%
Policy maker	13	7%
Scientist	96	54%
NGO member	5	3%
Other, please specify	18	10%
Total	177	100%

Q5. Where do you work?

Answer	Response	%
National management	40	34%
Sub-national management	15	13%
Community/Communal/Indigenous	2	2%
International	28	24%
University	17	15%
Other, please specify	15	13%
Total	117	100%

Q6. What position/level do you work at now?

Answer	Response	%
Field management	28	19%
Middle management	50	34%
Senior management	51	35%
Executive management	17	12%
Total	146	100%

Q7. What fishery or fisheries are you involved in? If you work with several fisheries, please pick one fishery. Should you wish to give information about more than one fishery, please take the survey again?

Answer	Response	%
Large pelagic	23	16%
Small pelagic	22	15%
Large demersal	36	25%
Small demersal	10	7%
Crustaceans	17	12%
Shellfish	2	1%
Inland fishery	3	2%
Aquaculture	4	3%
Coastal	12	8%
Shark	1	1%
Other	13	9%
Total	143	100%

Q8. How would you best describe the fishery you work in?

Answer	Response	%
Collapsed	10	6%
Highly overfished	15	9%
Overfished	49	28%
Sustainably fished	67	39%
Recovering	14	8%

Answer	Response	%
Developing/exploratory	4	2%
No information	13	8%
Total	172	100%

Q9. How many years of experience do you have in fisheries?

Answer	%
0–3 years	16%
3–5 years	10%
5–10 years	11%
10–15 years	14%
15–20 years	17%
20–25 years	17%
More than 25 years	15%

Q10. What are the major changes that have occurred in fisheries management during your career with fisheries? Multiple answers possible.

Answer	Response	%
There are no major changes	8	7%
Increased level of scientific input	60	55%
Increased level of industry input	53	49%
Increased level of NGO input	47	43%
Environmental versus fisheries department	40	37%
Level of collaboration amongst stake holders and organizations	51	47%
Increased number of staff	8	7%
Increased number of scientists	26	24%
Amount of resources (money, staff)	18	17%
Ecosystem based management instead of single species management	50	46%
Dealing with pollution (e.g., terrestrial run-offs like fertilizer, soil turbidity)	16	15%
Other, please specify	20	19%

Q11. In the last 5–10 years, have resources (such as funding, staff, research, equipment) for management overall:

Answer	Response	%
Increased a lot	5	4%
Increased a little	49	39%
Stayed about the same	35	28%
Decreased a little	25	20%
Decreased a lot	12	10%
Total	126	100%

Q12. Has the fishery you work with implemented Ecosystem-Based Fisheries Management (EBFM) or a similar holistic approach to governing fisheries?

Answer	Response	%
Yes	104	60%
No	68	40%
Total	172	100%

Q13. How well do you consider the overall implementation process of EBFM, or similar management approach, to have gone?

Answer	Response	%
Very successful	11	10%
Successful	32	30%

Answer	Response	%
Neutral	50	47%
Unsuccessful	13	12%
Very unsuccessful	1	1%
Total	107	100%

Q14. How satisfied are you with the Ecosystem-Based Fisheries Management process?

Question	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied	Total Responses
Planning process	11	47	33	9	4	104
Implementation process	8	40	30	23	3	104
Results	7	26	45	21	4	103

Q15. Briefly describe your experience with the implementation of EBFM.

Answer	Response	%
It still doesn't consider the whole ecosystem	30	36%
Lack in scientific knowledge delays proper implementation	19	23%
Highly complex procedure, which makes it hard to really implement EBFM	48	58%
Lack of compliance to secure successful EBFM	22	27%
Time consuming	19	23%
Difficult to decide what variables and what species (spp). Species should be considered as there are so many variables and spp in an ecosystem	28	34%
Insufficient compliance	10	12%
It has worked very well	6	7%
Improvements can already be seen	15	18%
It has been a satisfactory process	11	13%
Other	11	13%

Q16. How do you view the role of governance and management to fisheries in your country as well as worldwide? For each of the following variables, please say if you believe there is a need for more or less of the following variables.

Highly needed

Variables	National Fisheries	World Fisheries	Total Responses
Stronger political will to manage fisheries	98	131	229
Improved conservation measures	68	107	175
Enforcement of regulations	69	112	181
Change of governance structure	57	86	143
More money	59	81	140
More staff	51	74	125
More research	71	98	169
More international collaboration	83	116	199
Managing Illegal, Unreported and Unregulated fishing (IUU)	76	128	204

Somewhat needed

Variables	National Fisheries	World Fisheries	Total Responses
Stronger political will to manage fisheries	36	27	63
Improved conservation measures	56	46	102
Enforcement of regulations	50	39	89
Change of governance structure	58	55	113
More money	76	63	139
More staff	70	59	129

Variables	National Fisheries	World Fisheries	Total Responses
More research	65	51	116
More international collaboration	48	31	79
Managing Illegal, Unreported and Unregulated fishing (IUU)	47	30	77

Satisfactory as it is

Variables	National Fisheries	World Fisheries	Total Responses
Stronger political will to manage fisheries	19	5	24
Improved conservation measures	28	4	32
Enforcement of regulations	38	9	47
Change of governance structure	35	11	46
More money	28	10	38
More staff	38	19	57
More research	23	8	31
More international collaboration	21	9	30
Managing Illegal, Unreported and Unregulated fishing (IUU)	32	3	35

Less needed

Variables	National Fisheries	World Fisheries	Total Responses
Stronger political will to manage fisheries	8	3	11
Improved conservation measures	10	3	13
Enforcement of regulations	3	1	4
Change of governance structure	8	1	9
More money	3	2	5
More staff	6	2	8
More research	3	0	3
More international collaboration	7	2	9
Managing Illegal, Unreported and Unregulated fishing (IUU)	1	0	1

Q17. Why do you believe, on a global scale, we are still facing fisheries overexploitation in regulated fisheries? Drag and drop your rankings.

Question	Major Challenge	Some Challenge	Minor Challenge	No Challenge	Total Responses
There is not enough scientific information.	43	74	40	4	161
Scientific knowledge is not being used to its fullest.	90	49	21	2	162
Lack of political will.	133	25	10	0	168
There needs to be stricter laws and regulations.	74	63	24	4	165
There needs to be more compliance and enforcement of laws.	109	45	11	1	166
Management is focused on species rather than eco-based management.	81	58	20	5	164
General public does not care enough about sustainable fishing to make it worthwhile for politicians to make it a priority.	68	60	31	7	166
Fish abundance is too complex to predict.	39	70	50	7	166
Lack of formal harvest strategies	44	66	45	7	162
Environmental variables affecting fisheries abundance are too complex to measure and predict.	50	66	39	9	164
Commercial fishers have too much influence.	54	62	31	16	163
There is not enough scientific expertise to interpret scientific data on management level.	47	54	50	13	164
Lack of political knowledge on marine and fisheries related issues.	87	55	17	3	162
Other	18	2	0	0	20

Q18. What management tools are being and should be used to manage the fishery you work in?

Question	Tools Being Used	Tools That Should Be Used	Total Responses
Total Allowable Catch (TAC)	116	53	169
Individual Transferable Quota (ITQ)	66	47	113
Seasonal closures	104	68	172
Regional zoning	66	46	112
Spatial closures (e.g., MPA)	95	63	158
Spawning closures	69	60	129
Size limits	99	70	169
Commercial only fishing areas	19	23	42
Recreation only fishing areas	23	28	51
Ecosystem based management	67	73	140
Bag limits	38	36	74
Mesh size	75	53	128
Trawling net size restrictions	59	34	93
Fishing vessel size restriction	38	25	63
Horsepower restrictions	26	20	46
Tabu/Taboo	9	9	18
Bottom trawling is banned	34	33	67
Other gear restrictions	65	29	94
Fishing vessels buy backs by government	16	15	31
Fuel subsidies	35	18	53
Surplus fish purchases	11	22	33
Grants for new fishing vessels	18	12	30
Tax exemption programs	13	14	27
Vessel construction, renewal and modernization	20	15	35
Fishing access agreements	25	23	48
By-catch reduction device	59	46	105
Other	9	13	22

Q19. In your work, who is and who should be involved in the fisheries management process?

Question	Who is Involved?	Who Should be Involved?	Total Responses
Fisheries managers	148	86	234
Natural resource managers	75	80	155
Fishers	103	103	206
Politicians	130	67	197
Scientists	133	95	228
NGOs	80	78	158
The public	35	69	104
Local communities	36	79	115
Other	3	6	9

Q20. Here is a range of input controls used in fisheries management. Do you support/oppose the concept of?

Question	Strongly Support	Support	Neutral	Oppose	Strongly Oppose	Total Responses
Gear restrictions	105	43	16	1	1	166
Vessel size restrictions	51	40	38	30	4	163
Horsepower restrictions	38	35	50	35	5	163
Seasonal closures	107	45	12	2	0	166
Regional zoning	87	47	25	3	0	162
Recreational only fishing areas	42	33	56	24	6	161
Spatial closures	105	47	12	1	0	165

Question	Strongly Support	Support	Neutral	Oppose	Strongly Oppose	Total Responses
Spawning closures	109	37	14	1	0	161
Size limits	100	42	20	2	1	165
Commercial only fishing areas	38	36	58	28	0	160
BRDs (by-catch reduction device)	100	48	12	2	0	162

Q21. There is a range of output controls used in fisheries management. Do you support/oppose the concept of?

Question	Strongly Support	Support	Neutral	Oppose	Strongly Oppose	Total Responses
Total Catch Limits (TACs)	100	43	22	2	1	168
Individual Transferable Quotas (ITQ)	75	41	40	7	5	168
Bag limits	71	44	45	4	1	165

Q22. In your experience in fisheries, do you support/oppose the concept of?

Question	Strongly Support	Support	Neutral	Oppose	Strongly Oppose	Total Responses
Fishing vessels buy backs by government	40	64	30	25	9	168
Fuel subsidies	33	19	26	36	52	166
Surplus fish purchases	13	30	50	38	34	165
Grants for new fishing vessels	31	21	30	35	50	167
Tax exemption programs	29	26	36	31	44	166
Vessel construction, renewal and modernization	34	43	39	16	35	167
Fishing access agreements	57	61	38	7	4	167

Q23. How much do you estimate the fishery you work with costs to manage annually (US dollar)? Costs include research, management, subsidies.

Answer	Response	%
<US$500,000	11	7%
US$500,000–1 million	18	11%
US$1–$2 million	6	4%
US$3–5 million	16	10%
US$6–15 million	6	4%
US$16–20 million	6	4%
US$21–30 million	1	1%
US$31–40 million	1	1%
US$41–50 million	1	1%
US$51–60 million	2	1%
US$61–70 million	1	1%

Answer	Response	%
US$71–80 million	0	0%
US$81–90 million	2	1%
US$91–100 million	2	1%
US$101–150 million	1	1%
US$151–200 million	2	1%
US$200–250 million	1	1%
>US$ 250 million	4	2%
Local currency, if you wish	0	0%
Don't know	86	51%
Total	167	100%

Q24. Do you know how much revenue your fishery provide annually?

Answer	Response	%
Yes	39	31%
No	87	69%
Total	126	100%

Q25. How many fishing vessels operate within your fishery?

Answer	Response	%
1–5	19	13%
6–25	33	23%
26–50	22	15%
51–75	13	9%
76–100	5	4%
>100	50	35%
Total	142	100%

Q26. How many fishing vessels are registered in the country where you work?

Answer	Response	%
1–10	5	9%
11–30	1	2%
31–60	2	4%
61–100	2	4%
101–200	3	5%
201–400	3	5%
401–600	6	11%
601–1000	2	4%
1001–2000	8	14%
2001–5000	9	16%
5001–10,000	5	9%
10,001–20,000	7	13%
>20,000	3	5%
Total	56	100%

Q27. In your country, how important is fishing as a main food source of protein?

Answer	Response	%
Overall survival depends on fishing	12	7%
Vital for some regions/areas	39	23%
Somewhat important	46	27%
Not important for survival	71	42%
Total	168	100%

Q28. In your country, how important is fishing as a main source of income?

Answer	Response	%
Overall income depends on fishing	8	5%
Vital for some regions/areas	70	42%
Somewhat important	61	37%
Not important for income	27	16%
Total	166	100%

Q29. In your country, are there regions where fishing is the major economic activity?

Answer	Response	%
Yes, many regions	29	18%
Yes, a few regions	107	65%
Yes, one region	5	3%
No	24	15%
Total	165	100%

Q30. In your country, are there regions or areas where fishing is the major food source of protein?

Answer	Response	%
Yes	68	41%
No	96	59%
Total	164	100%

Q31. Are subsidies provided for fishers in the country in which you work (including fuel rebates, low interest loans, employment, buy-backs, reduced tax)?

Answer	Response	%
Yes	87	52%
No	56	34%
Don't know	23	14%
Total	166	100%

Q32. What type of subsidies are there?

Answer	Response	%
Fuel	75	88%
Lower interest on bank loans	22	26%
Employment payments from the government	30	35%
Cultural subsidies	13	15%
Other, please specify	22	25%

Q33. Do you believe these subsidies contribute to overcapacity of the fishing industry?

Answer	Response	%
Not at all	28	32%
Somewhat	34	39%
Significantly	22	25%
Don't know	3	3%
Total	87	100%

Q34. Who should carry the real cost of fish products? Costs include governance, management, research and monitoring of fisheries.

Answer	Response	%
Fishers	113	69%
Consumers	112	69%
Government	104	64%
Don't know	14	9%

Q35. The fishery I work with has:

Answer	Response	%
A single species management approach	57	37%
An ecosystem management approach	87	56%
Don't know	12	8%
Total	156	100%

Q36. In your experience with fisheries, which five (if any) fisheries management and governance regulations are the most efficient for Ecosystem-Based Fisheries Management?

Answer	Response	%
Food and Agriculture Organization of the United Nations code of conduct	7	6%
MPAs	63	52%
ITQs	59	49%
Gear restrictions	56	46%
Stakeholder participation	43	36%
Good science	64	53%
Co-management	30	25%
Closures	28	23%
No bottom trawling	25	21%
Stakeholders' education	23	19%
Size limits	10	8%
More legislation	8	7%
Assessment of implementations	25	21%
Spawning closures	11	9%
Mesh size	11	9%
TAC	31	26%
Monitoring	30	25%
By-catch Reduction Device (BRD)	35	29%
Other	20	17%

Q37. What type of organisation do you believe would be optimal to ensure successful Ecosystem-Based Fisheries Management (or the alike management)?

Answer	Response	%
Top-down management (centralised governance)	11	7%
Bottom-up management (communal, local)	13	8%
Mix of top-down and bottom-up management	132	83%
Don't know	7	4%

Q38. Decision making process; information and decisions. For the following statements, please indicate if you agree or disagree.

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Total Responses
In your role, the scientific information is easy to understand, interpret and apply.	23	74	18	47	2	164
You have an appropriate amount of information (scientific or otherwise) to make sound fisheries management decisions.	27	63	38	31	4	163

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Total Responses
You consider there are robust mechanisms to deal with assessing uncertainty.	13	64	29	56	2	164
You believe you can influence final fisheries management decisions.	15	65	27	40	16	163
You believe the current decision making process of your fishery is adequate for sustainable fisheries.	10	57	28	50	17	162
Do you believe the current decision making process of your fishery is adequate for an overall sustainable marine biodiversity?	10	45	34	56	17	162
Comment	1	1	0	2	1	5

Q39. What information or decision-making processes would you like to see more of when making fisheries or ecosystem management decision?

Answer	Response	%
Use of indicators in decision-making process	31	21%
More research about ecosystem processes and functions	41	28%
Politicians need to understand the science	62	42%
All stake-holder involvement	56	38%
Industry compliance of regulations	23	16%
Supporting fishers with knowledge and implementation of regulations	23	16%
Holistic objectives; marine and socioeconomic issues	34	23%
Use of EBFM models	29	20%
Decreasing IUU fishing	28	19%
Integrating fishing and environmental policies	44	30%
Political commitment	52	36%
Management transparency	56	38%
Other	13	9%

Q40. What variables are considered and should be considered when setting fisheries quotas?

Question	Variables That Are Considered	Variables That Should Be Considered	Total Responses
Size structure of the stock	117	81	198
Age structure of the stock	101	81	182
Catch data	122	73	195
Catch Per Unit Effort (CPUE)	106	67	173
Life history traits	60	86	146
Maximum Sustainable Yield	80	68	148
Maximum Economic Yield	37	52	89
Climate change	23	101	124
Recruitment	90	92	182

Question	Variables That Are Considered	Variables That Should Be Considered	Total Responses
Abundance	104	71	175
Mortality	94	73	167
Effects on the ecosystem	41	103	144
Other, please specify	7	16	23
Other, please specify	2	4	6
Other, please specify	2	2	4
Don't know	5	3	8

Q41. If any, what resources would you like to have more of in order to improve sustainable fisheries and marine biodiversity?

Answer	Response	%
Resources are already adequate	15	9%
Scientific knowledge	107	65%
Enforcement mechanisms	75	45%
Legal expertise and advice	35	21%
Collaboration amongst stake holders	105	64%
Collaboration amongst governmental departments	81	49%
Administration staff	10	6%
Other, please specify	20	12%

Q42. How would you assess management of the fishery you are involved in?

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Total Responses
Current management is sufficient to ensure the long-term sustainability of fishery	19	55	20	50	16	160
There needs to be stricter regulations on commercial fishing	25	46	29	50	9	159
There needs to be stricter regulations on recreational fishing	17	37	53	41	12	160
Current commercial fishing regulations are adequately enforced	14	53	29	49	17	162
Current management is sufficient to ensure the long-term sustainability of overall biodiversity	14	30	31	65	21	161
There are too many regulations	8	33	34	74	10	159
The regulations are too complex to manage, monitor and measure successfully	12	35	28	70	13	158

Q43. I would like to get some information on how satisfied you are with various aspects of your job. How satisfied are you with.

Question	Very Satisfied	Satisfied	Neutral	Dissatisfied	Very Dissatisfied	Total Responses
Level of access you have to scientific fishing data	27	80	17	37	4	165
Number of other managers working with you	11	54	61	29	1	156
Resources to manage in the best way you know	11	46	47	44	6	154
Collaboration with scientists	25	73	20	40	3	161
Getting messages across to the decision makers	7	37	28	70	20	162
Decisions based on scientific expertise	8	54	31	56	14	163
Level of influence you have on decision making	7	43	34	64	15	163
Level of application of your work	14	50	42	41	12	159

Q44. Do you believe that illegal, unreported and unregistered (IUU) fishing is a problem for your fishery?

Answer	Response	%
Yes	100	64%
No	57	36%
Total	157	100%

Q45. How much of the total catch in your fishery do you believe is due to illegal, unreported and unregistered fishing?

Answer	Response	%
None at all	4	4%
Less than 5%	11	11%
6–15%	20	21%
16–30%	21	22%
31–40%	14	15%
41–50%	15	16%
51–60%	6	6%
61–80%	0	0%
More than 80%	5	5%
Total	96	100%

Q46. Do you believe that illegal, unreported and unregistered (IUU) fishing is a problem within your country?

Answer	Response	%
Yes	107	66%
No	55	34%
Total	162	100%

Q47. How much of the total catch in your country do you believe is due to illegal, unreported and unregistered (IUU)?

Answer	Response	%
None at all	0	0%
Less than 5%	7	7%
6–15%	23	22%
16–30%	39	38%
31–40%	13	13%
41–50%	13	13%
51–60%	3	3%
61–80%	3	3%
More than 80%	3	3%
Total	104	100%

Q48. Do you believe that illegal, unreported and unregistered (IUU) fishing is a problem in some parts of the world?

Answer	Response	%
Yes	137	99%
No	1	1%
Total	138	100%

Q49. How much of the total catch world-wide do you believe is due to illegal, unreported and unregistered (IUU)?

Answer	Response	%
None at all	0	0%
Less than 5%	0	0%
6–15%	3	2%
16–30%	25	19%
31–40%	36	27%
41–50%	32	24%
51–60%	19	14%
61–80%	15	11%
More than 80%	4	3%
Total	134	100%

Q50. What are the key aspects of these IUU problems?

Answer	Response	%
Corruption	80	66%
Lack of data	53	44%
Poverty	52	43%
No or little governance in place	61	50%
No or little high seas controls	52	43%
Lack of international policies	34	28%
Lack of international compliance	46	38%
Fishers' data not accurate	57	47%
Growing human population	34	28%
Lack of political will	61	50%
Trawlers entering MPAs	11	9%
High demand for high-valued fish species	24	20%

Answer	Response	%
Recreational fishers	11	9%
Large black market	34	28%
Insufficient compliance	67	55%
Not enough awareness of the consequences	19	16%
Habitat destruction	23	19%
Other	7	6%

Q51. What approaches does your organisation use to measure fish abundance?

Answer	Response	%
No measures are used	10	6%
Catch Per Unit Effort (CPUE)	103	65%
Size	75	47%
Recruitment	58	36%
Fishers' log books	100	63%
Government trawling data	61	38%
Age structure	66	42%
Other, please specify	31	19%

Q52. What improvements are needed to obtain/maintain sustainable fisheries?

Answer	Response	%
No improvements are needed	10	6%
Stronger political commitment to marine ecosystem management is needed	119	72%
More regulation is needed	38	23%
More science is needed	88	53%
More enforcement is needed	96	58%
Higher reliability and quality of catch data is needed	85	52%
A higher level of ecosystem management is needed	88	53%
Consumers drive the market and are responsible for buying sustainable seafood	61	37%
Other	12	15%

Q53. How old are you?

Answer	Response	%
18–25	7	4%
26–34	31	19%
35–54	99	60%
55–64	25	15%
65 or over	3	2%
Total	165	100%

Q54. What is the highest level of education you have completed?

Answer	Response	%
Less than High School	0	0%
High School/GED	8	5%
Some College	6	4%
2-year College/University Degree	8	5%
3–4-year College/University Degree	24	14%

Answer	Response	%
Master's Degree	47	28%
Doctoral Degree	71	42%
Professional Degree (JD, MD)	4	2%
Total	168	100%

Q55. What is your degree in?

Answer	Response	%
Marine science	89	59%
Environmental science	30	20%
Business and Management	11	7%
Economics	4	3%
Law	4	3%
Political science	5	3%
Social science	5	3%
Other (please specify)	10	7%

Q56. What is your gender?

Answer	Response	%
Female	47	29%
Male	117	71%
Total	164	100%

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Consensus management in Antarctica's high seas – Past success and current challenges

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ABSTRACT

The high seas surrounding Antarctica have a vast and diverse marine environment. Following its establishment in 1982, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has managed the ecosystems of the high seas of the Southern Ocean. CCAMLR pioneered the ecosystem approach to resource management, took action on the problem of sea bird by-catch, and has established measures to combat illegal unreported and unregulated (IUU) fishing. CCAMLR is seen as an example of best practice in managing marine resources in international waters. At the same time, CCAMLR's challenges arise in the balance between 'fishing' and 'conservation' interests; for example in the current debates over climate change and marine protected areas in the Southern Ocean. In each of these examples, CCAMLR's consensus-based decision-making process has been a central element in shaping outcomes. This paper considers CCAMLR's achievements in sustainable marine ecosystems and identifies emerging challenges.

1. Introduction

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has managed the marine living resources in the Southern Ocean for over 30 years. The negotiating parties to the Convention were innovative when it pioneered an ecosystem approach to marine resource management [1,2] within the Convention on the Conservation of Antarctic Marine Living Resources. The Convention includes a focus on a precautionary approach and has an explicit focus on rebuilding exploited stocks. CCAMLR incorporates a consensus decision-making model that can provide challenges in the deliberations among the 25 CCAMLR Members [3]. This challenge is most notable in the current debate over the implementation of a representative system of marine protected areas within the Convention Area. Nevertheless, the consensus-based management approach has seen CCAMLR successfully negotiate complex management issues in a forum where Members have differing interests; that is between states focused on marine resource extraction and others focused on marine resource and environmental conservation. It should be noted that this dichotomy is not absolute, with Members supporting CCAMLR's mandate to balance extraction with conservation.

The paper outlines and assesses CCAMLR's achievements and identify key challenges it faces currently in addressing its core objectives around sustainable marine ecological systems in the Antarctic. We argue that, notwithstanding these challenges, CCAMLR provides a model governance regime for contemporary marine resources management, and the lessons learned in the development of this regime have broad application for other fisheries and regions [4].

2. International ocean governance and conservation of Antarctic marine life

Situated in the Southern Ocean, the Convention Area represents about 10% of the Earth's surface and surrounds the Antarctic continent. Commercial fishing of krill and fish species in the Southern Ocean commenced in the late 1960s and early 1970s [5]. Fishing in such distant and high latitude waters had been facilitated by industrialisation of fishing and developments in vessel design, catch processing, and in technological advancements in communication and navigation [6]. In the Southern Ocean, and elsewhere, industrialisation has been associated with greater

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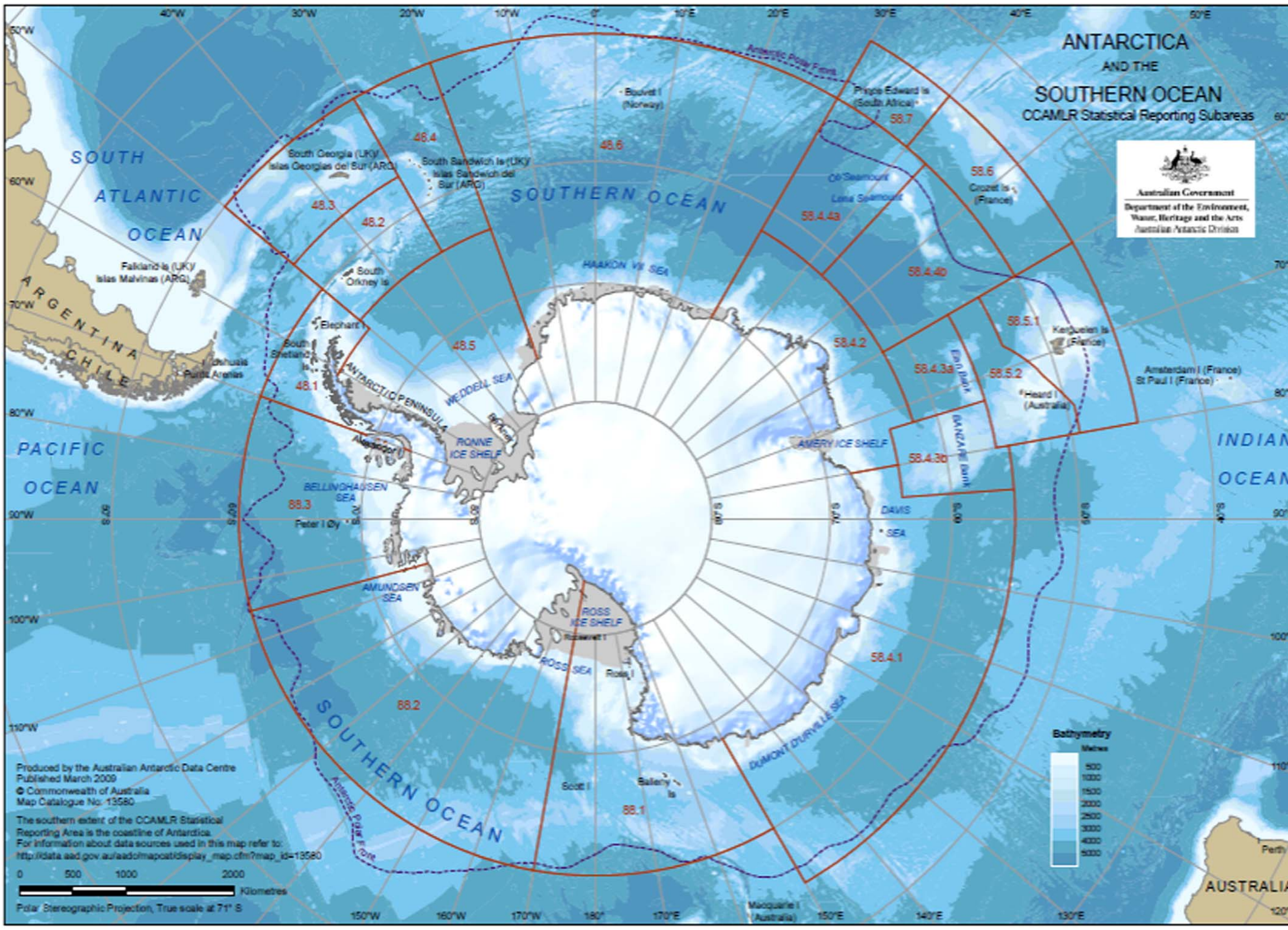

Fig. 1. The CCAMLR Convention Area, divided into subareas. Map courtesy of the Australian Antarctic Division and is © Commonwealth of Australia (2009).

investment in fishing gear, higher competition, increased effort, and greater mobility, which together typically leads to increased fishing pressure, often followed by overfishing [7].

In the 1970s concern was raised over increasing, and at that time unregulated, fishing for krill in the Southern Ocean. Krill were recognised as a keystone species, acting as an energetic link between primary production and higher trophic layers [8]. In addition to scientific concern over potential over-exploitation of krill stocks, several stocks of Antarctic finfish were heavily exploited as a result of limited controls on large scale commercial harvesting [8].

These unsustainable fishing activities initiated the negotiations within the Antarctic Treaty forums in 1978 in relation to Article IX '…preservation and conservation of living resources in Antarctica'. These discussions concluded with the adoption of the Convention at the Conference on the Conservation of Antarctic Marine Living Resources held in Canberra, Australia, 7–20 May 1980. The CAMLR Convention aimed to conserve Antarctic marine life in a high seas area covering some 32 million km^2 (Fig. 1) entered into force on 7 April 1982 [9].

To implement the Convention, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) was established by international treaty in 1982, with its secretariat located in Hobart, Australia. The CAMLR Convention established a Scientific Committee to provide advice to the Commission, based on the best available science. While the Commission is the final decision-making body, Article IX (4) of the Convention states 'In exercising its functions … the Commission shall take full account of the recommendations and advice of the Scientific Committee.' Today CCAMLR has 25 acceding Members, including the European Union, with a further 12 countries as contracting parties to the convention. The 25 decision-making Members are represented in and have the right to participate in deliberations of the annual meetings of the Commission and the Scientific Committee, pay an annual membership fee, provide scientific research to the Commission's Scientific Committee, and may be involved in marine resource harvesting.

From its initiation, CCAMLR's main objective has been the 'maintenance of ecological relationships between harvested, dependent and related populations', utilising a new 'ecosystem approach' to fisheries management [9]. It has been described as a conservation organisation with the attributes of a regional fisheries management organisation [10]. The Convention was the first international initiative to commit to monitoring a large marine ecosystem [11]. In 1990 a moratorium on all finfish fishing was adopted by the Commission, aiming to conserve the remaining fish stocks [12]. The Convention excludes management of whales (which are managed under the International Convention for the Regulation of Whaling (1946) through the International Whaling Commission (IWC)), and seals (which are managed under the Convention for the Conservation of Antarctic Seals, CCAS (1972)).

3. Fisheries of the Southern Ocean

Fishers in CCAMLR's Convention Area currently target Patagonian toothfish (*Dissostichus eleginoides*), Antarctic toothfish

(*Dissostichus mawsoni*), mackerel icefish (*Champsocephalus gunnari*) and Antarctic krill (*Euphausia superba*). The Scientific Committee and its subsidiary body, the Working Group on Fish Stock Assessment, annually assess the fisheries in the Convention and recommend TACs to the Commission. The catch limits are believed to be set at precautionary levels [13,14], yet recent research by Abrams et al. (2016) suggests that due to knowledge gaps with associated uncertainties the TAC for the toothfish fishery in the Ross Sea is not set at a precautionary enough level [15].

3.1. The krill fishery

The pressure on the krill stock has been low following the withdrawal of Soviet Union flagged krill vessels in the early 1990s [8]. In 2013 the Commission agreed on a krill catch limit; of 620,000 t (estimated to be 1% of the total krill biomass), with a reported catch of 217,357 t at the end of the season [16]. Recent expansion of markets (particularly for krill oil and aquaculture feed), with new fishing methods and harvesting techniques and potentially new fishing grounds due to melting sea ice [17], has attracted more vessels to this fishery. The possibility that Members may exert upward pressure on krill quotas in the future cannot be ruled out. Another challenge in managing krill is the sheer magnitude of the stock, with the biomass, currently estimated to be just under 400 million tonnes, may fall within the range of 60–420 million tonnes [18].

3.2. Toothfish

Both species of toothfish are believed to be fully exploited in the Convention Area and depleted in some parts of the Indian Ocean due to IUU (illegal, unreported and unregulated) fishing [13,19]. Being highly priced, toothfish is particularly vulnerable to IUU fishing.

3.3. Mackerel icefish

Mackerel icefish was heavily fished in the 1970s and 1980s, and in the early 1990s the fishery was closed out of concern over high annual variability in catches and continuous high exploitation [16]. Reviewed annually, icefish is today harvested cautiously at South Georgia and at Heard and McDonald Islands. Overall icefish is believed to be fully exploited [13].

4. CCAMLR and fisheries management

Following the entry into force of the CAMLR Convention, there have not been any documented collapses in fisheries managed by the Commission. Moreover, previously depleted stocks of toothfish have been rebuilt to the point that the Australian toothfish fishery received the Marine Stewardship Council eco-certification in 2012 and a 'best choice' label from the Monterey Bay Aquarium's Seafood Watch program in 2013. This indicates that the management approaches and tools in place to date are considered to be in line with global best practice. Nevertheless past overfishing has left its stamp, with species such as the marbled rockcod (*Notothenia rossii*), a stock heavily fished prior to the establishment of the CAMLR Convention, showing no sign of recovery despite the fishery having been closed for over 30 years [13].

5. Assessing CCAMLR's achievements

CCAMLR's management of fisheries links commitments to conservation with strong governance through conservation measures. In meeting these commitments CCAMLR is seen as a leader in regional fisheries organisations [4,20]. Four main factors stand out as contributing to these outcomes: a focus on science and decision-making using monitoring of indicator species; addressing IUU fishing; addressing incidental catch – particularly of seabirds; and last, but by no means the least significant, geopolitical factors.

5.1. Monitoring for management

CCAMLR's commitment to the ecosystem-based approach to fisheries management demanded new tools and methods [21]. One criticism is that, despite such a commitment, it took almost a decade for the Commission to move to address the practical aspects of such an approach [1]. In 1989 CCAMLR established the CCAMLR Ecosystem Monitoring Program (CEMP) to consider the impact of fishing on dependent predator species, especially with regards to krill-dependent predators [5]. As there is a large number of researchers from many different countries involved in data collection, the CEMP also facilitated the standardisation of research methods. Further, research methods are regularly assessed and updated as necessary by CCAMLR's Working Group on Ecosystem Monitoring and Management, ensuring timely uptake of new research technologies such as those supporting remote sensing (e.g. satellite imagery, remote cameras) [22].

For many higher predators in the Southern Ocean (such as mammals, penguins, sea birds, fish and squid) krill is the primary source of food [23]. Krill's foundational role in the Antarctic marine food web and its accessibility for monitoring saw krill become a focus of monitoring by the CEMP [22]. Other species monitored include the Adélie penguin (*Pygoscelis adeliae*), chinstrap penguin (*P. antarctica*), gentoo penguin (*P. papua*), macaroni penguin (*Eudyptes chrysolophus*), black-browed albatross (*Thallasarche melanophrys*), Antarctic petrel (*Thalassoica antarctica*), cape petrel (*Daption capense*), and Antarctic fur seal (*Arctocephalus gazella*) [22].

5.2. Addressing 'illegal fishing'

During its 34-year history, the Commission has governed the Convention Area by implementing binding Conservation Measures on its Members, supported by non-binding resolutions. The Conservation Measures and Resolutions address a range of areas including harvest controls, gear, vessel monitoring, fishing notifications, data reporting, landings, and by-catch [24].

IUU occurs in high seas as well as in exclusive economic zones (EEZ), in waters of developing and developed nations, and by registered as well as by unregistered vessels [25]. The term IUU fishing was developed by CCAMLR, which was the first fishery organisation to explicitly address IUU fishing, with CCAMLR Members moving the item to the FAO and to wider attention [26,27]. Being a highly valued species, toothfish in the CCAMLR managed Convention Area has been the target for IUU fishing, and in the 1990s it was estimated (based on IUU vessel sightings by legal fishing vessels) that the actual catch was six times larger than what was reported by authorised vessels [28]. Although still a concern, the IUU challenge is now controlled (Fig. 2), as the result of the adoption of a range of measures including surveillance, enforcement and market controls. These measures include IUU sighting reports; IUU vessel lists; recovery of IUU fishing gear; port and at-sea inspections; a Catch Documentation Scheme for toothfish (tracking catches from landing through the trade cycle); a compulsory Vessel Monitoring System on all vessels fishing in the CCAMLR-managed area; and support for Members surveillance and prosecution of IUU activities [28].

There are sixteen vessels on CCAMLR's IUU list, which was

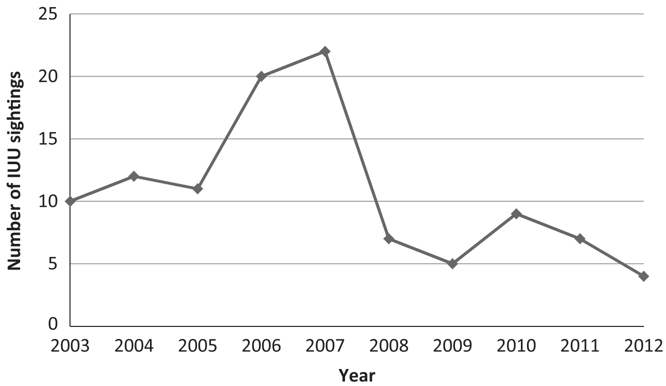

Fig. 2. Number of IUU vessel sightings reported to CCAMLR [28].

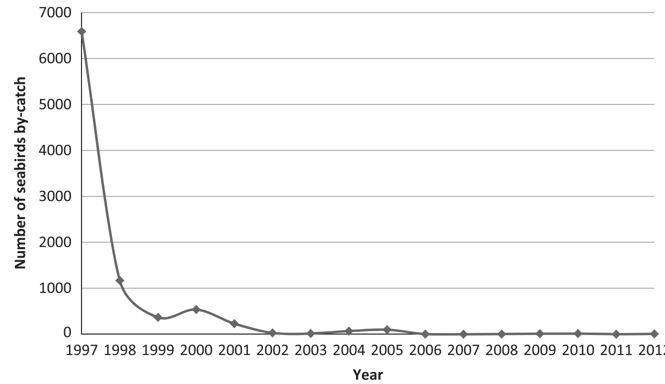

Fig. 3. Incidental seabird by-catch mortality from demersal longline fishing for toothfish in the Convention Area [37].

established in 2003. Most of these vessels have been documented as fishing illegally several times and over many years [16]. Based on the number of reported vessels, IUU fishing in the Convention Area has decreased, but it is clear that it is difficult to monitor and measure IUU fishing based on vessel sightings alone (the Secretariat stopped reporting these sightings in 2012). Using market based data and industry sourced information, COLTO (The Coalition for legal Toothfish Operators) estimated that the IUU catch for toothfish by six identified IUU vessels during 2014/2015 season was between 1264 and 1500 t [29]. In 2014–15 and 2015–16 action by Sea Shepherd Conservation drew attention to this small but persistent IUU activity targeting toothfish. A range of enforcement actions and international cooperation has targeted these six vessels performing small but persistent IUU fishing of toothfish.

Unreported catch by legal vessels is not included in any official statistics. For icefish and toothfish fisheries there is a requirement that an international observer is to be present for all fishing operations on all boats (i.e. 100% coverage), whilst the krill fishery requires 50% observer coverage, using either international or nationally appointed observers [30]. In a break from standard practice within national EEZs, these observers are required by CCAMLR to report on scientific measures only (although Members may ask their observers to collect more data). The observers do not monitor the catches and are not required by CCAMLR to ensure that vessels comply with Conservation Measures (indeed they have no power to enforce compliance), nor are they actually required to report IUU catches.

While legal fishing vessels in the Convention Area are required to report any unidentified vessels, not all such vessels are reported [28]. There is also potential misreporting of catch by legal operators. One example is that the Korean *Insung No. 7*, which was found to have breached two Conservation Measures; namely exceeding the regional catch by more than 300% (135.7 t catch vs 40 t limit) and catching 35 t after the Master received notice they had exceeded the catch limit [31]. When the Commission agreed to place this vessel on the IUU vessel list, Korea (a CCAMLR Member) refused to support the move, thereby permitting *Insung No. 7* to continue fishing in the Convention Area [32].

Another challenge is that there is differing capacity to deal with illegal activities of Members. Transparency International's Corruption Perceptions Index (how likely a country is to be corrupt) indicates that three of CCAMLR's Members rate as 'highly corrupt', 11 have a moderate rating and the remaining 11 are rated close to 'clean' [33]. Countries where corruption is more or less accepted as part of business may be less able to follow Conservation Measures in practice even though they officially have agreed to them.

5.3. *Addressing incidental catches of seabirds*

In response to the increasingly documented by-catch of seabirds, CCAMLR adopted Conservation Measure, 29/X, in 1991 (now named Conservation Measure 25–02). The recorded seabird by-catch has since dropped from 6600 birds in 1997 to close to zero in 2012 (Fig. 3) [34,35]. This large decrease is due to a combination of new Conservation Measures, making it compulsory for fishing vessels to use streamer lines aimed at keeping birds away from the vessels, as well as using weighting of baited hooks to make hooks sink quickly so as not to attract attention from foraging birds [35]. The Commission has also defined some initiatives on how fishers may manage marine debris so as not to harm seabirds. One such initiative is to process offal discharge on-board the vessels [36].

While this reduction in seabird mortality is worthy of credit, incidental catch of seabirds may not have been completely eradicated, as it may still be occurring on IUU vessels. Work to restrict IUU fishing will therefore likely also help in reducing seabird mortality.

5.4. *Geopolitical factors and consensus-based management*

The remoteness of Antarctica, which makes it costly to fish in its waters, and the extreme weather conditions might be factors indirectly providing some protection to the Southern Ocean resources and associated ecosystems. Antarctica is the windiest and coldest place on earth, with wind gusts above 200 km/h and the average annual temperature near the coast of −10 °C, dropping to below −40 °C in the winter [37]. Even though the CCAMLR fisheries are open all year around, extreme cold and wind in winter provide challenges for fishing. During the summer other challenges to operating at high latitudes arise from icebergs and sea ice.

International politics also play a major role in Southern Ocean management. Part of the CAMLR Convention Area is located within the Antarctic Treaty Area. The Antarctic Treaty states in its first article that '*Antarctica shall be used for peaceful purposes only*'. Further, Article IV of the Antarctic Treaty (replicated in the CAMLR Convention) removes territorial disputes or conflicts: *'No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim or enlargement of an existing claim, to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force.'*.

These particular geo-political conditions provide strong support for collaborative action. The differing interests amongst CCAMLR Members can, however, mean that consensus-based management is challenging, as every single Member has to agree to a proposal and Members do not have to forward a particular reason when disagreeing. This often time-consuming process has been criticised for hindering appropriate responses to conserve a constantly changing marine environment [38]. Conservation Measures often include details that might take several years to negotiate and to adopt [39]. CCAMLR retains a strong normative commitment to the ecosystem approach yet it is valid to question the strength and robustness of this commitment in terms of fisheries management, the MPA, and climate change proposals (especially given the rapidity of climate related change).

6. What is next? Some current challenges

The Southern Ocean is one of the fastest changing regions globally, with average temperatures having already risen by close to 1 °C [40,41]. To cope with this degree of change Antarctic ecosystems will need to be exceptionally resilient [42]. Conserving living marine resources is a highly complex task where the effects of climate change needs to be mitigated. Another challenge involves controlling fishing pressure (including IUU fishing) and its impact on the ecosystem, which must continue to be the focus of attention to provide Antarctic ecosystems with as much adaptive capacity as possible.

6.1. How many fish are there?

Governing fisheries using the ecosystem-based approach demands that fishing does not suppress any stocks within the ecosystem to levels that reduce survival or reproductive success. Despite the Commission's largely positive fisheries record in recent years, challenges remain. Therefore, and in accordance with Article II of the Convention, a core task for CCAMLR is to estimate the biomass effects from fishing pressure within each of the statistical areas, subareas and divisions of the Convention Area. Once these estimations have been identified sustainable TACs can be set. Bioenergetics models used to reach those estimations of total prey consumption ask for data on the number of individuals in a population, the energetic demands of each individual and the diet composition [43,44].

The Commission aims to set precautionary catch limits using the stochastic generalised yield model (GYM) [45], which only models a single species. Another issue using the GYM is that the estimations of pre-exploitation biomass and the annual TACs do not incorporate the 10-fold inter-annual variability of krill abundance and biomass [46], leaving no validation system and thereby no mechanism to compensate for unexpected low recruitment due to unknown environmental variables, perhaps including climate change. These challenges have been recognised by the Commission and, for krill, integrated assessment models were first implemented in 2011 [47]. This was again brought up at a CCAMLR symposium in Chile 2015, suggesting that more focus on the links of the Antarctic food webs needs to be considered when setting TACs so to move away from single species stock assessment [48]. However, for the Commission to adopt a multi species modelling approach to further implement a full EBFM approach all Members would need to agree to do so. Even without taking such a step, the variables in the GYM include recruitment variability, growth and mortality but not how these variables might be affected by climate change or ENSO events [46].

It is not as if CCAMLR does not recognise its challenges. At the CCAMLR symposium in Chile 2015 some Members proposed that to take the ecosystem-based management approach further, work on whole ecosystem relationships would need to be undertaken as this is essentially absent from CCAMLR's work today [48]. At the Symposium it was further noted that CCAMLR should consider ways to achieve a robust management framework for CCAMLR high seas fisheries, including the use of multi-year management plans and a revision of the principles and procedures for new and exploratory fisheries [48].

Questions have also arisen around monitoring methods. The Southern Ocean is a very challenging environment in which to work, and new sustainable effective monitoring methods are always being sought (e.g. satellite counts of penguin colonies) [23]. This has seen collaboration with fishing operators as a means of collecting information required for stock assessments. To estimate the abundance of toothfish, CCAMLR uses a capture-recapture method, where fishers during their fishing excursions are encouraged to tag and release, and to report on all recaptures [49]. While this can be considered a sensible means of getting extra information it has been noted that it is insufficient by itself for setting sustainable Total Allowable Catches (TACs) [50].

The Working Group on Fish Stock Assessment acknowledges that there was a vast difference in the amount of tags released and recovered among the vessels, and suggests that training of fishers and scientific observers could be a solution [28]. In the Fishery Report from 2013, it was acknowledged there are some key uncertainties about the stock assessment and in the SPMs [Spatial Population Models] of Antarctic toothfish (*D.mawsoni*), including knowledge in movement patterns associated with spawning, developing toothfish distribution and abundance information in areas closed to fishing. Some suggestions regarding how to address these issues have been considered [28]. Moreover, simulations have suggested that *Dissostichus eleginoides* (Patagonian toothfish) has experienced varied levels of overfishing, and research catches show that it could take decades for depleted stocks to recover, even when the fishery is closed [51]. These simulations also showed that even small levels of research catch can delay the recovery of the toothfish stock significantly.

As noted much of the current management practice is still primarily focussed on single species management. While work is being done on integrated ecosystem models this its is not always clear that this work addressed into the commission's decision making process [52]. Nonetheless, CCAMLR's precautionary approach, its regular monitoring programs and data analysis provide robust fisheries governance [53], especially in comparison with the management of other high seas fisheries.

6.2. Monitoring 32 million km^2 of international waters

Despite representing a systematically collected dataset covering almost 30 years, the CCAMLR Ecosystem Monitoring Program (CEMP) covers a small number of sites and with no mechanism to translate the monitoring results into Conservation Measures or other management strategies [13]. This, and the lack of a feedback management system based on these variables has been recognised by the Commission [47] and it would be encouraging to see greater spatial coverage in Members monitoring programs, with varying temporal and spatial scales. The vast amount of rather detailed data needed to set ecosystem-based TAC is a demanding task. To fully achieve EBFM, CCAMLR would need to address the temporal and spatial indifferences within CEMP as the length of foraging trips and breeding success may be affected by weather conditions, food availability and anthropogenic stressors such as fishing. CEMP would also need to monitor larger areas and include more detailed data of the Southern Ocean. A monumental (and at present likely infeasible) task given current resource and technology constraints.

Given krill's potential sensitivity to climate change induced environmental shifts (discussed further below), there is a recognised need to incorporate short and long term aspects of climate change effects on the abundance of krill when setting TACs; increase the research effort to more sites; and find a way to feed the information from this kind research into a more adaptive ecosystem based management system, which could in turn help improve the monitoring and the resilience of Antarctic ecosystems.

6.3. The establishment of marine protected areas

In 2005 CCAMLR committed to progress work towards a representative system of MPAs within the Convention Area by 2012. One example of the challenge with consensus-based management is the Commission's difficulty in adopting proposed new Conservation Measures on the establishment of Marine Protected Areas (MPAs) in the Convention Area. Establishing MPAs in the Convention Area is seen to support the Commission's broad mandate to rebuild fish stocks and they could also serve as reference areas for monitoring anthropogenic impacts (e.g. harvesting and climate change) occurring in the Southern Ocean.

CCAMLR has consistently addressed the marine environment as part of its focus on its ecosystem approach [10]. The commission responded to international concern over protecting vulnerable marine ecosystems (VMEs) through development of precautionary practices and then specific conservation measures for designation and management of VMEs within the CCAMLR Area [10].

In 2009, the Commission implemented an MPA by making the southern Atlantic on the South Orkney southern shelf an MPA (proposed by the UK), covering 94,000 km^2. In 2011 CCAMLR adopted Conservation Measure 91–04 (CM 91–04) 'General framework for the establishment of CCAMLR Marine Protected Areas'. Proposals to implement MPAs in east Antarctica and the Ross Sea were first proposed in 2012. Five Commission meetings later (including a special meeting in Bremerhaven, Germany, in 2013) they have not yet been adopted. The original MPA proposal off the Antarctic Peninsula submitted by the EU and the UK in 2012, aiming to protect newly exposed habitats due to the collapse of ice shelves, was withdrawn during the same meeting through lack of support. In an attempt to approve the attractiveness of a Ross Sea MPA, New Zealand and the US amalgamated their proposals for the region (also at the Commission meeting in 2012), creating the Ross Sea Region MPA (RSRMPA) proposal. This proposal covers 1.57 million km^2, with over 1 million km^2 as a no-take. It was unsuccessful in 2012 and was again presented at the 2015 Commission meeting. The East Antarctic Region MPA (EARMPA) proposal submitted jointly by Australia, the EU and France currently represents 946,998 km2. During the 2015 Scientific Committee meeting a new MPA proposal, the Weddell Sea MPA, was presented for consideration by Germany. At the time of writing discussions are ongoing around the surviving MPA proposals.

Conservation Measure (CM) 91–04 was adopted in 2011 in accordance with the Convention (Article IX), to provide a framework for the establishment of MPAs in the Convention Area, stating that '*This Conservation Measure and any other CCAMLR Conservation Measures relevant to CCAMLR MPAs shall be adopted and implemented consistent with international law, including as reflected in the United Nations Convention on the Law of the Sea*', and '*CCAMLR MPAs shall be established on the basis of the best available scientific evidence, and shall contribute, taking full consideration of Article II of the CAMLR Convention where conservation includes rational use*' [47]. During the 2014 and 2015 meetings Japan submitted a proposal to standardise a procedure to establish MPAs. This was opposed by several Members at both meetings on the basis that CM 91-04 includes substantial and adequate details for the creation of an MPA proposal [54,55]. Should Japan's proposal, if presented again, be passed by the Commission it could further delay any MPA implementation as 1 the content of the standardised procedure would need to be defined and then agreed on by all Members, and 2) the already existing MPA proposals would have to be rewritten with potentially more (and new) information required. It could thereby be seen as a strategy to delay MPA measures by Members more interested in fishing than conservation, rather than a genuine effort to secure a procedure for implementing them.

This failure to reach consensus on the establishment of MPAs in the Convention Area could be interpreted as damaging CCAMLR's reputation and being the result of vested interests and concerns of particular Members related to access to fishery resources. This shows that consensus decision-making can create delays and additional challenges, possibly leading to delegates deciding against presenting some proposals believing consensus is unlikely. Other delegates observe, however, that the consensus process holds everyone accountable to the decisions made [56] and any agreed action is typically successfully implemented [57]. This means that action on new CMs calls for considered and lengthy diplomatic negotiations to gain support from Members (any of whom may choose to block a proposal). This is because measures adopted by the Commission not only guide the future of Antarctic marine ecosystems, but also affect a Member's economic, social and political interests. The MPA proposal currently being developed by Germany for the Weddell Sea is an area of high interest to krill fishers [58]. It will be interesting to see whether additional MPA proposal(s) will facilitate the stated intention by the Commission to implement MPAs, or lead to deadlock through failure to gain consensus.

Discussion over establishing MPAs in the Convention Area has occurred for more than ten years now. It should be recognised that a failure to reach international consensus does not preclude nations acting in their own territories. For example, MPAs have already been implemented in claimed Antarctic territories: in 2002 Australia created a 71,200 km^2 Marine Reserve off the Heard Island and McDonald Islands Territory (extended in 2014); South Africa established an MPA in the Southern Ocean in 2009 in their EEZ, surrounding Prince Edward and Marion Islands 200 km south of South Africa, covering 180,633 km^2; France established MPAs off the Crozet (6650 km^2) and Kerguelen (6000 km^2) Islands in 2006; and in 2012 the UK implemented the largest (at the time) MPA in the world in South Georgia and Sandwich Island covering 1,070,000 km^2.

6.4. Adapting to climate change

The Southern Ocean plays a vital role in the uptake of anthropogenic carbon dioxide, absorbing nearly half of the world's anthropogenic CO_2 emissions [59]. The waters of the Antarctic Circumpolar Current, the largest current on Earth, surrounds the Antarctic continent and it is this water that has warmed, on average, more than any other part of the global ocean [42,60,61]. The Southern Ocean is a region undergoing rapid environmental change and variability, with extreme patchiness in ice contraction, growth and seasonal dynamics [62]. In the Antarctic and Southern Ocean climate change is impacting a number of areas, especially the Antarctic Peninsula, with evidence that 87% of the glaciers on the Antarctic Peninsula have retreated in recent decades [63]. This, together with the collapse of ice shelves/ice tongues, can have significant implications for ice dependent species. For example, krill is dependent on sea ice during all its life stages. In addition, the duration, areal extent and thickness of ice are ecological parameters which have major implications for the reproduction and survival of krill, and thus the many marine species dependent on krill as food [46,64]. Moreover, the increased accessibility of areas that now have reduced ice cover can lead to new areas and species being exposed to fishing with no conservation measures in place to protect them [65].

Ocean acidification (OA) is another challenge to the ecosystems in the Southern Ocean [66]. Driven by the absorption of excess atmospheric carbon, oceanic waters are becoming more acidic, with aragonite saturation already approaching corrosive levels for unprotected calcifiers in the Southern Ocean [67,68]. Although not all taxa are equally vulnerable, some pteropods (e.g. *Limacina helicina Antarctica*) found in the Southern Ocean are already show shell pitting, highlighting their susceptibility to acidification [68,69].

Individually, ocean acidification and climate driven changes in temperature present challenges to Antarctic fauna and flora, but it may be the cumulative effects of their combined change which is most telling. Before the direction shifts of climate change the Southern Ocean could be considered a relative stable (if somewhat extreme) environment and so species inhabiting it may not be able to cope with the degree of change and variability they will face under the combined pressures of climate change and ocean acidification. Between the warmest and the coldest habitats in the Convention Area there is a difference of only about 7 °C and krill, therefore, has not needed to adapt to high variability in temperature changes. This means krill has a low tolerance to temperature change. and research shows, that even a small change of 1–2 °C, can have a fundamental impact on krill recruitment, distribution, behaviour and other physiological performances [70]. In addition, laboratory experiments have shown that the level of acidification forecast could halt embryonic development of krill [71]. For other crustaceans (in their natural environment) an increase in OA has been seen to affect growth, survival and recruitment as a result of diffusion of CO_2 across the gills [72,73]. Ocean acidification may also negatively affect the production of new exoskeleton, a process that takes place throughout a krill's life, and thereby jeopardise survival [46]. Consequently, the combined effects of climate shifts and OA could see all aspects of krill life history under attack, ultimately potentially leading to a reduction in the importance of krill to southern ocean ecosystems [74]. This could have profound implications for Southern Ocean ecosystems, because changes to krill abundance can have cascading effects through much of the Antarctic food web [75].

One example of change to the ecosystem due to climate change that is already evident is on the western side of the Antarctic Peninsula, which has experienced the fastest rates of climate change recorded anywhere on the planet over the past 35 years [65,76,77]. Research shows that this warming of the ocean has coincided with a decline in krill stocks and phytoplankton in the entire Atlantic sector of the Southern Ocean [46]. The documented decrease in sea ice cover [76] has also caused the decline in the ice dependent Adélie penguin, which has moved southwards [78].

Apart from climate change, climate anomalies such as El Niño Southern Oscillation (ENSO) and the Southern Annular Mode may further induce stress on the Antarctic ecosystems affecting, for example, recruitment and survival of Antarctic marine species [77,79].

CCAMLR Members have responded to these emerging issues. During the Commission meeting in 2015 EU proposed special protection for areas that affected by retreating sea ice or iceberg collapse around the Antarctic Peninsula. The EU also presented a proposal to limit coastal krill fishing during penguins and seals breeding periods. Norway and the UK proposed a non-binding resolution on the inclusion of relevant views on climate change in all scientific documents that contributed to CCAMLRs work.

None of these three proposals were adopted by the Commission. A proposal to appoint an intercessional task force to consider climate change in a CCAMLR perspective, was, however, adopted [55].

There was a resolution adopted by CCAMLR in 2009 to consider the effects of climate change on Southern Ocean ecosystems [80]. Given CCAMLR's history of leading the introduction of the ecosystem approach to management, it may come as a surprise that of CCAMLR's five scientific working groups none is specifically related to climate. The Commission has not as yet adopted a climate change adaptation plan, as seen for example in the plans and strategies for the Great Barrier Reef in Australia [81], the Arctic [82] and the US fisheries [83].

6.5. The changing face of CCAMLR

It is not only the biophysical side of the Antarctic waters that is dynamic. CCAMLR is periodically reviewed and the Performance Review of 2008 reflected that when CCAMLR was established, less than 40% of its Members were fishing nations, compared with a majority today. As a result, Members' delegations include officials from Fisheries Ministries rather than from Ministries of Foreign Affairs or from Ministries of Environmental Protection [84]. Co-management in fisheries has been shown to foster successful management [85–87], but issues arise over the direct or indirect influence of fishing companies participating during the Commission's annual meetings [88].

As the Scientific Committee is charged with presenting the best science available as the basis for its advice to the Commission, the scientific work undertaken by Members is of major importance. The CCAMLR Performance Review identified issues concerned with the science that contributes to management, raising concerns that only a minority of Members regularly submit scientific papers or are involved in regular scientific expeditions collecting data for the benefit of conserving wildlife [89]. Australia and the UK together account for 33% of the Member papers submitted to both the Commission and the Scientific Committee [88]. Adding the US papers, these three countries provide 54% of the total papers submitted over the last 30 years. Other active Members include Chile, France, New Zealand, Russia and South Africa [88]. This highlights that the original CCAMLR Members have a significantly higher commitment to providing scientific findings and adopting Conservation Measures than those Members that joined at a later stage. A similar trend has been observed within the Antarctic Treaty [67]. Interestingly, Korea, Norway, Poland, Spain and Uruguay who are among the most active fishing Members, have submitted less than 6% of the papers [88]. This skew in participation may reflect differing capacities to execute science in such extreme conditions, but may also reflect differing priorities (e.g. in fishing, conservation, or a mix of the two) [88]. This is not a new challenge. Research has shown that Members opposing submission of routine data are also those who oppose the adoption of Conservation Measures by arguing there is not sufficient data to support such a measure [1].

6.6. Other issue areas

Apart from the challenges identified above (implementation of MPAs, setting precautionary catch limits, filling scientific knowledge gaps, mitigating the effects of climate change and manoeuvring consensus management) there may be other pressing challenges ahead, external to but impacting on CCAMLR. Although there is a prohibition on oil and gas extraction under the seabed within the Antarctic Treaty Area, this issue may be on the horizon as an outcome of Members' claims to sovereignty rights over sea bed resources, such as oil and gas. Nations that have made submissions to the United Nations Commission on the Limits of the Continental Shelf regarding shelf claims offshore of their Antarctic territories, include Argentina Australia, Chile, France, New Zealand and the United Kingdom. Norway has made a reservation for the right to do so [90]. Further, a submission by Russia to the XXXIV Antarctic Treaty Consultative Meeting in 2011 declared that achieving the Russian Federation's scientific objectives would support to 'strengthen the economic capacity of Russia through the use of marine biological resources available in the Southern

Ocean, and complex investigations of the Antarctic mineral, hydrocarbon and other natural resources' [91].

7. Conclusions

There are more than 10,000 species in the Southern Ocean, and managing its ecosystems involves considering a large number of variables that may be changing at a fast rate. CCAMLR is globally acknowledged for its work on ecosystem-based management in the high seas surrounding Antarctica. CCAMLR's work over 34 years highlights the range of challenges in managing the Southern Ocean using the ecosystem approach. Differing priorities and interests among Members ensure that it will continue to be a lively and dynamic (and on occasions frustrating) exercise. This process is unfortunately unlikely to get easier as the commission faces increasing challenges from the impacts and influence of climate change, ocean acidification and potentially increased fishing pressure on the region.

Shifts in species abundance and distribution are evident [65]. Concern over the cumulative stressors of fishing, climate change, ocean acidification and UV radiation will impact on the abundance of krill and thereby the whole food web have been expressed by several scientists [71,73,92–94]. CCAMLR's future successes will be measured by its ability to respond to these stressors.

An ecosystem approach relies on provision of supporting data to ensure appropriate indicators can detect changes due to fishing [95]. It is likely that the effect of fishing pressure on seabirds may not have been detected were it not for several seabirds being indicator species in CEMP. That the impact of fishing on seabirds was recognised and CCAMLR's Members acted, endorsing Conservation Measures to mitigate incidental mortality of seabird bycatch, is a CCAMLR success story. The decrease in IUU fishing is also an example of CCAMLR's ability to effect change. Ongoing vigilance is required, however, with continued measures to combat illegal fishing in the waters surrounding Antarctica vital for sustainable marine environments.

CCAMLR has rightly been seen as a leader in marine resources conservation for many years. It does face ongoing challenges in fulfilling its mandate to ensure conservation/rational use of Antarctic marine living resources. Lack of consensus over the direction of marine conservation is possible. Failure to gain agreement on the implementation of MPAs during five Commission meetings could be seen as a warning sign that the organisation's overall commitment to marine conservation is facing significant challenge, or it could be a manifestation of the time consuming processes that are a part of international politics and governance. Is this a warning that CCAMLR is managing to the 'lowest common denominator' approach? Although there are many positives with a consensus-based management approach, it is also a risky way to govern large, highly complex and rapidly changing environmental processes, particularly where it is well known that climate change is already impacting the Southern Ocean.

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